Central Banker to the World: Foreign Reserve Management and U.S. Money Market Liquidity*

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Abstract

We develop a model showing how foreign reserve management decisions can have adverse effects on U.S. money market liquidity. Consistent with events during the March 2020 dash-for-cash, in the model, as export volatility increases, a foreign central bank shifts its reserves out of relatively illiquid Treasuries and into a Fed reverse-repo facility. Under a fixed Fed balance sheet, these precautionary moves drain liquidity from U.S. money markets and push repo spreads higher. The model's predictions provide a credible channel to identify the effect of foreign central bank demand for dollar liquidity on repo spreads, exploiting the characteristics of commodity exporters with pegged exchange rates. Our empirical evidence indicates that precautionary sales by these central banks in lead to a statistically significant and economically relevant widening in repo spreads. These results underscore how the Fed's foreign-repo facilities mitigate global dollar-funding stress and protect U.S. short-term funding markets.

Keywords: Treasury market, repurchase agreements, market liquidity, liquidity premium, exorbitant privilege, fixed exchange rate regime.
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1 Introduction

In March 2020, amid the global financial turmoil induced by the COVID-19 pandemic, foreign official institutions contributed to severe dislocations in U.S. Treasury and money markets by selling more than $100 billion in U.S. Treasuries. In response, the Federal Reserve not only purchased Treasuries as part of market functioning operations, but also introduced the Foreign and International Monetary Authorities (FIMA) repo facility, enabling a broad set of foreign central banks to access dollar liquidity. The introduction of this facility raises a broader policy question: When should the Federal Reserve provide liquidity to foreign central banks?

We address this question with a two-country model with financial frictions in which a foreign central bank pegs its currency to the dollar and faces volatile export revenues. In our framework, the foreign central bank chooses between holding U.S. Treasuries, which we assume are relatively illiquid in stress, and keeping deposits at the Federal Reserve, which serve as the ultimate liquid buffer. When export revenues become uncertain, the central bank boosts its dollar deposits and funds them by selling Treasuries. Because the Fed's total assets are fixed in the immediate short run, every additional dollar parked by the foreign bank tightens the pool of reserves available to private financial intermediaries, driving up repo spreads. The model thus pinpoints a clear mechanism that links foreign reserve management to U.S. money-market stress. While the Fed can counteract this effect by purchasing the Treasuries sold by the foreign central banks *ex post*, our model shows that introducing a standing repo window—mirroring the FIMA facility—can remove the incentive for these precautionary Treasury sales *ex ante* while increasing demand for U.S. Treasuries.

Using the structure our model provides, we exploit oil-exporting countries with dollar pegs as a clean laboratory: option-implied oil-price volatility delivers plausibly exogenous shocks to liquidity demand among oil-producing country central-bank liquidity demand, and official accounts hold most of these countries' Treasuries at the Fed. We therefore instrument interest-rate differentials with oil volatility and show that a one-standard-deviation shock leads these central banks to sell roughly $2 billion of long-term Treasuries and boost their Fed balances. Consistent with the model's predictions, these shifts correspond to a 2-6 basis-point widening of core U.S. repo spreads—large moves in markets where daily changes are typically measured in fractions of a basis point.

Our analysis is motivated by the most severe Treasury-repo dislocation since the Great Financial Crisis. In March 2020, foreign official accounts emerged as one of the largest sellers of U.S. Treasuries—second only to mutual funds—offloading some $147 billion, of which central banks accounted for over $100 billion (Vissing-Jorgensen (2021); Banegas et al. (2021)). Several studies document how these sales exacerbated Treasury illiquidity during the COVID-19 shock (e.g. Duffie (2020); Barth and Kahn (2020); Vissing-Jorgensen (2021); Banegas et al. (2021); Weiss (2022)). We show much of the proceeds from these sales was redirected into more liquid assets, notably the Federal Reserve's foreign repo pool. Our model illustrates this portfolio rebalancing aggravated dollar liquidity strains in two ways. First, domestic dealers—acting as market makers—absorbed the sold Treasuries onto their balance sheets, increasing their funding needs. Second, when foreign official accounts parked sale proceeds in the Fed's foreign repo pool, they effectively withdrew reserves from the system, further tightening the supply available to fund Treasury purchases and widening money-market spreads

These portfolio decisions matter because international intermediaries face intraday reserve-management frictions (e.g. Poole (1968); d'Avernas and Vandeweyer (2020); Bianchi and Bigio (2022)). In our model, these frictions give rise to endogenous liquidity premia: when intermediaries must meet settlement balances in both the United States and the foreign economy, reserves become especially valuable. A foreign central bank that sells Treasuries to build up its Fed deposits thus drains reserves from the broader system, driving up dollar funding rates. This mechanism yields sharp predictions: terms-of-trade shocks that increase export volatility should raise precautionary demand for dollar liquidity abroad and, in turn, widen U.S. money-market spreads.

We use the model's predictions linking export volatility, liquidity demand, Treasury sales, and money market spreads to develop an empirical framework that allows us to reach causal conclusions about the effect of foreign central banks' Treasury sales on U.S. liquidity. We propose option implied oil price volatility as an instrument to isolate the effect of liquidity demand by foreign central banks in oil exporting countries with a fixed exchange rate. This identification strategy relies on independent evidence indicating that oil supply is highly inelastic in the short run for geological and technological reasons, specifically at the daily and weekly frequencies we consider. Global demand shocks and news are, therefore, the likely drivers of high-frequency changes in oil prices and volatility. Both are plausibly exogenous with respect to reserve managers' decisions. We also include a comprehensive set of control variables in the regressions to eliminate possible violations of the exclusion restriction, including news about oil supply derived from Organization of Oil Exporting Countries (OPEC) announcements and macroeconomic news. While our chosen laboratory of oil exporting countries with a fixed exchange rate might seem particular, this identification strategy sheds light on foreign reserve demand and liquidity in the U.S. Treasury and repo markets more broadly, where exogenous variation in liquidity demand is challenging to establish credibly.

Using forward-spot exchange rate-implied interest rate differentials vis-á-vis the U.S. to gauge high frequency reserve management pressures, we establish an empirical link between the liquidity demand of foreign central banks, oil price volatility, and spreads in U.S. repo markets. As oil volatility increases, the central banks of the oil-exporting countries sell Treasuries and hold more deposits for precautionary reasons, consistent with the model's predictions. These portfolio decisions coincide with widening interest-rate differentials with the United States, providing further support for the causal chain suggested by the model. The liquidity demand of foreign central banks is associated with an increase in oil volatility, which causes spreads in the U.S. repo market to rise substantially. Thus, in the absence of observable dollar liquidity demand, our model enables us to characterize the motive underlying demand using a directly observable variable. Our empirical estimates indicate that a one standard deviation increase in interest rate deviations caused by higher oil volatility leads to a two to six basis points increase in spreads in overnight money markets. We also find evidence that the mechanism through which these demand shifts affect U.S. liquidity is consistent with the model's logic, insofar as these countries' balances in the foreign repo pool rise with oil price volatility.

The two-country model we develop builds on research relating capital flows to exchange rate movements in the presence of financial frictions (Krugman, 1999; Aghion et al., 2004; and Blanchard et al., 2005). We study the role of financial frictions on the exchange rate and capital flows, similar to Gabaix and Maggiori (2015), Akinci and Queraltó (2018), and Bianchi et al. (2021). Our model is closest to Bianchi et al. (2021). Unlike that paper, however, we examine the foreign central bank's portfolio problem and how it responds to terms-of-trade shocks.

Foreign central banks' precautionary demand for U.S. dollars is also the topic of Das et al.

(2022). That paper studies how stricter ex-ante financial regulations reduce the externality associated with non-U.S. central banks holding inefficiently large amounts of U.S. dollar reserves to mitigate the risks of a domestic financial crisis. By contrast, we focus on how the precautionary demand for dollars can act as a conduit for transmitting liquidity shocks to U.S. money markets.

Our work relates to research examining how strains in global dollar funding markets manifested themselves in March 2020 and how policymakers can mitigate the effects of those strains, such as McCauley and Schenk (2020), Goldberg and Ravazollo (2021), Aizenman et al. (2022), Bahaj and Reis (2021), and Ferrara et al. (2022). In particular, Choi et al. (2021) discuss the introduction of the Foreign International Monetary Authorities (FIMA) Repo Facility in March 2020 as part of the Federal Reserve's package of facilities to alleviate the dislocations in Treasury and U.S. money markets. Our paper provides strong, intuitive theoretical support for the facility. Introducing a FIMA repo facility into the model reduces foreign central banks' precautionary demand for dollar liquidity by lowering the cost of securing settlement balances for the foreign central bank, increasing U.S. liquidity. The facility also reduces the passthrough of increases in net export volatility in the foreign economy to U.S. liquidity. These findings underscore the rationale for the Federal Reserve to provide liquidity to foreign central banks, given its responsibility for maintaining orderly U.S. money markets.

The events of March 2020 provide specific examples of the spillover effects of foreign reserve management on U.S. money markets and demonstrate how real economic shocks can propagate to short-term funding markets in the United States. However, they are stark and extreme examples from which it is impossible to draw general conclusions. By contrast, our paper provides evidence on the size of the effect of central bank liquidity demand on U.S. money markets in general, using a credible identification strategy in as long a time series as possible.

Furthermore, our paper relates to work examining the relation between foreign Treasury holdings and Treasury prices (Bernanke et al., 2004; Warnock and Warnock, 2009; Bertaut et al., 2012; and Wolcott, 2020). This research focuses on foreign holdings' impact on Treasury yields. Warnock and Warnock (2009) and Wolcott (2020), for example, find that greater foreign demand for Treasuries is associated with lower yields. Our paper extends the logic of this research to other important asset prices by examining the impact of foreign Treasury sales on broader U.S. domestic liquidity. In this way, we turn the usual question about the effects of dollar illiquidity on emerging-market economies (EME) on its head. Instead of asking how market stress affects liquidity conditions and monetary policy in EMEs, we ask how foreign reserve management policies in EMEs can cause U.S. money market illiquidity.

In the next section, we discuss the Treasury sales by foreign official accounts in March 2020, which is a motivating example for our analysis. In Section 3, we document several stylized facts about foreign exchange reserve management in select oil-exporting countries. We then develop the model in section 4. In section 5, we discuss the assumptions behind our empirical framework and report the evidence from the regression analysis. We offer some conclusions in Section 6.

2 Motivation: Foreign official Treasury sales in March 2020

We use the March 2020 dash for cash to highlight the economic mechanism relating foreign central banks' reserve management decisions to U.S. money market liquidity. Several papers examine the effects of the dash for cash on Treasury market liquidity and volatility and the market dislocations the COVID-19 shock caused (Duffie, 2020, Schrimpf et al., 2020, Barth and Kahn, 2020, and Vissing-Jorgensen, 2021). The dash for cash also provides a stark example of the effect of central banks' demand for dollar liquidity on U.S. money markets and, at the same time, demonstrates why studying this single event without further identifying assumptions limits what we learn about the quantitative significance of this effect.

Figures 1 - 3, along with Tables 1 and 2, document stylized facts about foreign official sales and liquidity premia in U.S. money markets in March 2020. Figure 1 shows the sizes of Treasury sales in March by country, ranked from the largest seller to the largest buyer, using data from the Treasury International Capital (TIC) System. The most significant Treasury sales did not come from the two largest holders of Treasuries (China and Japan) but rather from Saudi Arabia. Other oil exporters, such as the United Arab Emirates, Kuwait, Oman, Iraq, and Bahrain, were also large sellers. Those countries sold \$39.3 billion in Treasuries, of which Saudi Arabia sold almost \$25 billion.

An important qualification to this observation is that the TIC sales include transactions from foreign official accounts and private holders of Treasuries—foreign official Treasury sales by country are not directly observable. However, oil exporters' central banks and other official accounts likely dominated the amount of Treasuries sold. Although international banks are active in oil-exporting countries, it is unlikely that banks' operations in those countries focus on intermediating Treasury flows for asset managers and other buy-side clients in the same way that the international banks based in New York and London do.

Next, Figure 2 shows that Treasury sales and liquidity premia increased as the spread between the Secured Overnight Funding Rate (SOFR) and the interest rate on excess reserves (IOER) widened in late February and early March 2020. Repo rates subsequently fell following the Federal Reserve's expansion of the repo facility and resumption of Treasury purchases on March 15 (Barth and Kahn, 2021). Meanwhile, foreign reserve managers' Treasury sales declined after the creation of the FIMA repo facility on March 31. That facility allowed reserve managers temporarily to convert Treasuries to cash through repo transactions.

Table 1 shows foreign official Treasury sales for the entire TIC System sample and various relevant country subsamples. Net foreign Treasury positions fell by about $261 billion in March, with a decline of $147 in foreign official accounts.[1] Foreign official accounts primarily sold longer duration off-the-run Treasury bonds, where liquidity problems in the Treasury market were the most severe. Long-term Treasury sales by foreign investors totaled $252 billion or around 97% of total sales and $124 billion (84%) of sales by foreign official accounts.

Countries with oil production per capita in the top third of the distribution sold more Treasuries than any other group, accounting for 41% of total Treasury sales. Table 2 also shows that the top oil producers sold three times more Treasuries than the low- or middle-oil production per capita bins.[2] Controlling for whether the sale came from a hedge-fund domicile country or an East Asian country, column 3 suggests that non-oil producing countries sold more Treasuries than low-oil production economies, but well below the amount that high-oil production countries sold.[3]

[1]Unlike other TIC data, the series from the Major Foreign Holders of Treasuries data set likely exclude hedge funds domiciled abroad. They are derived from the Form SLT survey that collects data directly from U.S. end-investors such as hedge funds and requires that U.S. feeder funds report holdings on their behalf from master funds domiciled in money centers such as the Cayman Islands. By contrast, the data derived from the TIC surveys are based on transactions with U.S. broker-dealers that are frequently unable to assess the end investor in a fund (Bertaut and Judson, 2023).

[2]We merge oil production per capita from the Energy Information Administration with the data on total Treasury sales and divide the countries into those without oil production and equally sized bins of low, middle, and high-oil production per capita. For each bin, we compute the total sales of long-term Treasuries and average sales by countries within the bin.

[3]We adjust the average Treasury sales data by regressing each country's long-term Treasury sales on dummies for low, middle, and high oil production and dummy variables for hedge-fund domicile countries and East Asian

How can we link these patterns in the data? Primary dealers are required to make reasonable markets for sales of Treasuries by these accounts. As Figure 3 suggests, however, in March 2020 the funds from the Treasury sales were primarily invested in the Federal Reserve's foreign repo pool, which is how the sales influence repo market liquidity. When a domestic agent sells Treasuries to a dealer and invests the proceeds in a domestic bank account, the funds remain available to the dealer to fund a Treasury purchase through the repo market. However, when a foreign seller invests the sale proceeds into the foreign repo pool, reserves are removed from the system, making repo financing of Treasuries more expensive. Foreign official Treasury transactions change the composition of the liability side of the Federal Reserve's balance sheet but not the asset side, which the Federal Reserve generally only expands or contracts during quantitative easing and tightening operations. Furthermore, even if the Federal Open Market Committee (FOMC) did conduct asset purchases or sales to offset changes in foreign repo pool balances, there would be a lag between changes in the foreign repo pool and changes in the Federal Reserve's asset holdings. During that time, changes in the foreign repo pool could affect reserves and funding availability because the size of the Federal Reserve's asset holdings is fixed. Figure 4 outlines the chain of transactions linking foreign official Treasury sales to repo market liquidity.

In summary, we learn from the foreign official accounts' Treasury sales in March 2020 that those originating from oil exporters with dollar pegs sold less liquid, long-term Treasuries and reallocated their holdings to more liquid assets. Those sales were correlated with a substantial reduction in liquidity in the repo and Treasury markets, pointing to a connection between the foreign official Treasury sales and repo market illiquidity.

The March 2020 dash for cash, however, is a single event that had extreme consequences for Treasury and repo market liquidity and does not represent the general patterns in the data. Additionally, the confounding effects of Treasury sales by different types of investors during the dash for cash and the Federal Reserve's introduction of several liquidity facilities create challenges for identifying the causal relation between reserve managers' portfolio management decisions and

countries. The hedge-fund domicile countries are Bermuda, the British Virgin Islands, the Cayman Islands, Ireland, and Luxembourg (also see Vissing-Jorgensen, 2021). Hedge funds, many of which are domiciled in those countries, sold large quantities of Treasuries in March 2020 (Schrimpf et al., 2020, Barth and Kahn, 2021, and Kruttli et al., 2021). The East Asian countries are China, Hong Kong, Macau, South Korea, Taiwan, Thailand, and Vietnam, whose sales may have decreased because of a slowdown in real activity, as Weiss (2022) suggests. We also include real GDP in the regression.

U.S. money market liquidity.

Therefore, to obtain a complete picture of the effects of dollar liquidity demand by the foreign official sector on U.S. money market liquidity and credibly identify the size of the effect, we use stylized facts about oil exporters with fixed exchange rates to develop a model relating reserve manager portfolio decisions to U.S. money market liquidity. The model provides a framework for identification and guides our empirical analysis of these linkages over the entire period for which data are available.

3 Stylized facts on reserve management by oil exporters

In this section, we investigate the relation among exchange rates, the current account, and foreign official Treasury sales. Motivated by events during the COVID-19 pandemic, we focus on countries with a pegged exchange rate and substantial oil exports. We focus on countries with an exchange rate peg to the dollar because the explicit policy goal of an exchange rate peg makes it easy to discuss the need to intervene in the foreign exchange market. Table 3 lists the countries in the TIC holdings data with pegged exchange rates, as classified by the IMF's 2020 Annual Report on Exchange Arrangements and Exchange Restrictions. The second column lists countries classified as oil exporters by the U.S. Treasury. The remaining countries with dollar pegs are predominantly Caribbean banking centers, except for Belize, which provides many banking services to U.S. clients. Because we are interested in Treasury sales caused by shocks affect exports and the terms of trade, we focus on oil exporters.[4] For the empirical analysis, we restrict the sample to countries with an active forward exchange rate market, which excludes Iraq. These restrictions leave us with five countries: Bahrain, Oman, Qatar, United Arab Emirates, and Saudi Arabia. Table 4 provides summary statistics of various characteristics of these countries.

[4] In principle, we could extend the analysis to other commodity exporters who assign some weight to targeting their exchange rates. However, it is challenging to find another country or group of countries that matches our identification strategy. Chile is a primary commodity exporter, but it only intervenes in the foreign exchange market sporadically to limit exchange rate volatility (Ilzetzki et al., 2019). Brazil is another plausible candidate as it exports oil, but it is also a major exporter of soybeans and iron ore, making its terms of trade related to shocks that affect those markets. It is important for the validity of our identification strategy that we are confident about what exactly the driving force is that leads to the Treasury sales. That assumption is most likely satisfied for countries with fixed exchange rates that are exposed to common shocks affecting their export demand and terms of trade.

3.1 Exchange rate management

Each country in our sample has historically managed its exchange rate with remarkable precision. Table 5 presents the official pegs for each country and the distribution of the market exchange rate reported by Refinitiv Eikon from November 1990 to October 2020. Exchange rates are expressed as local currency per U.S. dollar. During the entire thirty-year period, exchange rates were essentially constant. Across countries, the 90th and 10th percentiles are never more than 0.002 dollars away from the peg. This evidence suggests that the exchange rate pegs are highly effective and credible.

Although spot exchange rates have stayed close to the official peg, the currencies do experience fluctuations in the forward market. We calculate forward exchange rate deviations against the current exchange rate using three-month exchange rate swaps:

$$x_{i,t,m} \equiv \frac{F_{i,t,m}}{e_{i,t}} - 1 \tag{1}$$

where $F_{i,t,m}$ is the m-month forward exchange rate for country i at time t and $e_{i,t}$ is the spot exchange rate. We define $x_{i,t,m}$ to be the implied interest rate differential, and it has some useful properties. Under covered interest parity (CIP):

$$x_{i,t,m} = \frac{r_{i,t,m} - r_{\text{USD},t,m}}{1 + r_{\text{USD},t,m}} \approx r_{i,t,m} - r_{\text{USD},t,m}$$

where $r_{i,t,m}$ is the currency i return on an m month risk-free asset. Under uncovered interest parity and with no expected revaluations of the currency, $x_{i,t,m}$ is zero.

We construct the empirical counterpart to the forward exchange deviations using exchange rates and three-month forward exchange rates from Eikon. The panel spans 2005 to 2021. We annualize the exchange rate differences to obtain implied interest rate differentials. In Table 6, we present the empirical distribution of these differentials. Although the median of the differentials is near zero, there is a wide range. The United Arab Emirates' differentials range between -7% and 4%, while Oman's differentials range between -4% and 5%. The largest deviations occur during the financial crisis and the COVID-19 crisis. But even if we exclude the period from 2007 to 2009 and the first two quarters of 2020 from the sample, the differentials can be as large as 4%.

In Figure 5, we present the time series of the differentials normalized by their standard deviation. Several commonalities are evident. All series had large deviations during and immediately following the 2007-2009 financial crisis. Furthermore, oil deviations increased dramatically during the 2010s, when between June 2014 and January 2016 Brent oil prices fell from $111.03 per barrel to $33.14 per barrel. Finally, for several currencies, differentials also increased in 2020, most notably for Oman.

Table 7 shows that these interest rate differentials are also highly correlated across countries. The lowest correlation is 47% between the United Arab Emirates and Oman, and most correlation coefficients are above 60%. We take the first principal component of these five countries' normalized forward deviations to exploit the common variation across countries and reduce the effects of minor errors in the spot exchange rates. The first component accounts 69% of the daily variance in deviations. The explantory power of the first principal component is insensitive to excluding episodes such as the financial crisis.

There are two interpretations of what the implied interest rate differentials represent under covered interest rate parity. First, they could represent deviations from uncovered interest rate parity, such as a divergences between the three-month risk-free rate in one of the sample countries and the three-month risk-free rate in the United States. Second, they could represent speculation on low-probability revaluations of the country's currency. In our model, we adopt the former interpretation. The model shows how the interest rate differentials are related to financial flows and the availability of foreign and domestic liquidity when intermediation is constrained and thus linked to Treasury sales and the current account. Even under the interpretation that such deviations represent expectations of rare revaluations, we still expect them to correlate with Treasury sales to defend the peg and oil price movements that make such a revaluation necessary.

3.2 Exchange rates, Treasury sales, and oil prices

The evidence from March 2020 and the behavior of the forward exchange deviations motivate our analysis of the empirical relation among oil price volatility, measured using Brent options, implied interest rate differentials, and oil exporters' Treasury sales. We start with the relation between implied interest rate differentials and oil volatility on a country-by-country basis. Table 8 shows the daily correlation coefficient for each country between option-implied oil volatility and interest rate differentials, regressing interest rate differentials (in basis points) on option-implied oil volatility from 2012 to 2021. Despite the daily frequency at which the data are sampled, the correlation coefficients range from 11% to 30% across the different regressions. The estimated coefficient associated with oil volatility is statistically significant and positive, implying higher oil volatility moves in line with higher interest rates in oil exporters relative to U.S. rates. We also examine the daily relation between the various forward differentials with the first principal component, which we will call the interest rate factor or IR factor. The IR factor correlates highly with the individual countries' exchange rates, which is unsurprising given the high correlations among exchange rates. There is a 30% correlation with option-implied Brent volatility at a daily frequency and a statistically significant relation between the two series in a regression.

Figure 6 shows the relationships among oil volatility, interest rate differentials, and Treasury sales from 2012 to 2022. Each series is standardized to have mean zero and unit standard deviation in the sample period. The three series appear closely related. Periods of high volatility in oil markets such as June 2014, January 2016, and March 2020 coincide with relatively high implied interest rate differentials and extended periods of large Treasury sales by these countries. At monthly frequency, the correlation coefficient between interest rate differentials and option-implied Brent volatility is 72%, while the correlation coefficient between the IR factor and Treasury sales is 52%. These figures suggest a strong, albeit unconditional, statistical relation among the three series.

To interpret the relations among oil price volatility, implied interest rate differentials, and Treasury sales, we develop a structural model that relates these three variables to each other and provides a channel through which foreign official account Treasury sales affect U.S. money market liquidity.

4 Model of foreign reserve management and dollar liquidity

We develop a two-period, two-country model to relate the different stylized facts to each other and highlight the economic channels that connect them. There are three main actors in the model – an oil exporter, the United States, and international banks that intermediate financial flows between the two countries. The oil exporter and the United States each have a representative household and a central bank. The household in the oil-exporting country owns the oil wells that produce the oil that it and the U.S. consumer demand. The oil exporter's central bank pegs its exchange rate to the dollar. The United States produces the consumption good. The fixed number of wells and consumer demand determine the oil price, subject to taste shocks that determine the oil exporter's net exports.

A continuum of international banks stand between the oil exporter and the United States and intermediates their financial flows. The international banks accept deposits from the oil exporter and the United States, using them to purchase the oil exporter's and U.S. reserves and invest them in U.S. Treasuries. The international banks pass on profits to the oil exporter's household that, for simplicity, owns them. When banks decide whether to hold reserves or Treasuries, they face deposit requirements in the oil-exporting country and the United States that generate liquidity premia embedded in the returns on reserves. The deposit requirements are thus the financial friction that gives rise to the demand for dollar liquidity.

4.1 Oil Exporter and U.S. Households

We assume that the two periods in the model are on a short enough time horizon that consumers in the oil-exporting country and the United States have an inelastic demand for oil producer-denominated ("riyal") deposits ($D_t = \bar{D}_t$) and domestic deposits ($\tilde{D}_t = \tilde{D}$) that are invested through an intermediary. The U.S. household can also hold Treasuries directly in quantity $\tilde{B}_t$ but demands them elastically. Both households discount at a rate β.

Net exports are a random variable $\mathrm{NX}_t \sim N(0, \sigma_Z)$, and the consumer in each country is subject to lump-sum taxes τ_t, $\tilde{\tau}_t$ that fund each government. In Appendix A, we consider conditions on the consumers in the United States and oil-producing country necessary for these assumptions to hold in general equilibrium, but they are not the main mechanisms that drive the model's predictions. The financial sector faces inelastic demand for deposits from these two consumers. Without loss of generality, we assume that net exports are zero in the first period and focus on the effects of net exports and the variance of net exports in the second period.

4.2 International banks

A continuum of international banks indexed on the interval $[0, 1]$ intermediates between the oil exporter and the United States. Each bank has a U.S. headquarters and a subsidiary in the oil-exporting country, over which it makes joint decisions. The banks are open in the morning and evening of the first and second periods. In the morning, the oil-exporting subsidiary takes riyal deposits D_t, while the U.S. headquarters takes dollar deposits, $\tilde{D}_t$. The bank then decides whether to allocate the funds from deposits to riyal reserves, M_t, U.S. reserves, $\tilde{M}_t$, or holdings of U.S. Treasuries, B_t.

Intermediaries face an intra-day liquidity problem, similar to Poole (1968), d'Avernas and Vandeweyer (2020), Bianchi and Bigio (2022), and Bianchi et al. (2021). In the evening, three shocks affect the banks. The first two are idiosyncratic deposit shocks Z_t and $\tilde{Z}_t$, both of which are normally distributed with mean zero and standard deviation σ_Z. These shocks reallocate deposits across banks within a country. The third is an independent aggregate exchange shock, S_t, that reallocates deposits between dollars and riyals, which we assume is also normally distributed with mean zero and standard deviation σ_S. In the evening, exchange markets are closed for banks, and banks cannot convert Treasuries to reserves of either currency. In the oil-exporting country and the United States, however, banks are subject to the reserve requirement:

$$e_t(\tilde{M}_t + \tilde{Z}_t + \tilde{L}_t) + S_t \geq \theta e_t \tilde{D}_t \qquad\qquad M_t + Z_t - S_t + L_t \geq \theta D_t$$

If the reserve requirement is not met in the afternoon, banks borrow from the central bank through loans, L_t, which we assume comes at a penalty rate c over the interest rate on reserves for each country. The expected required loans from the central banks in the afternoon give the banks' demand for deposits and reserves in the morning:

$$\mathrm{E}\left[L_t\right] = L(\theta D_t - M_t) = \int_{-\infty}^{\theta D_t - M_t} (\theta D_t - M_t - X) dF(X)\, dX \tag{2}$$

where X denotes the total shock facing F is the cumulative distribution function of the total deposit shock, which is distributed with mean zero and variance σ_X and has a probability density function f.

The bank balances the cost of the loans against the returns on the various assets it holds. Banks are risk-neutral and live for only one period. These assumptions lead to the maximization problem:

$$
\begin{aligned}
\mathrm{E}\left[\pi_{t+1}\right] = \max_{B_t, D_t, \tilde{D}_t, M_t, \tilde{M}_t} & \mathrm{E}\left[e_{t+1} y_t\right] B_t + \mathrm{E}\left[e_{t+1}\tilde{\delta}_t\right] \tilde{M}_t + \delta_t M_t - \mathrm{E}\left[e_{t+1}\tilde{r}_t\right] \tilde{D}_t - r_t D_t \\
& - c\,\mathrm{E}\left[L_t\right] - \mathrm{E}\left[c e_{t+1}\right] \mathrm{E}\left[\tilde{L}_t\right] \\
\text{such that:} \quad & e_t B_t + e_t \tilde{M}_t + M_t = e_t \tilde{D}_t + D_t
\end{aligned}
\tag{3}
$$

where r_t is the return on riyal deposits, δ_t is the return on riyal reserves, $\tilde{r}_t$ is the return on dollar deposits, $\tilde{\delta}_t$ is the return on dollar reserves, and Y is the return on Treasuries. The constraint in the problem is the morning budget constraint for banks, which reflects their issuance of dollar and riyal deposits, purchases of foreign and domestic reserves, and Treasuries.

To focus attention on net exports and financial markets in the second period, we assume that the first-period realization of S_t is zero with certainty. This assumption simplifies the model's dynamics because it implies that net demand for foreign exchange from banks is zero in the first period.

4.3 Federal Reserve

For simplicity, we fix the Federal Reserve's monetary policy. It has a fixed balance sheet $\bar{A}$ that backs dollar reserve holdings by international banks and the oil exporter's central bank holdings of deposits with the Fed:

$$
\bar{A} = \tilde{M}_t + M_t^C \tag{4}
$$

This assumption implies that the Federal Reserve does not respond to shocks that lead to sales by the oil exporter's central bank. In practice, this assumption is most likely satisfied in the short run, which is the time horizon to which the model applies. Over the medium or long run, the Federal Reserve can adjust its reserve supply.

Similarly, we assume that there is an externally determined supply of Treasuries, $\bar{T}$, so that the oil exporter's central bank, international banks, or the U.S. household hold Treasuries:[5]

$$\bar{T} = B_t + B_t^C + \tilde{B}_t$$

We assume that demand for Treasuries from U.S. households is perfectly elastic. This assumption is not crucial to the model's results, but it simplifies the analysis.[6]

4.4 Oil-exporter's central bank

Our objective is to relate this situation to the asset holdings of the oil-exporting country's central bank. In light of the empirical evidence, we assume that the oil exporter's central bank has access to two assets: U.S. Treasuries it holds in quantity B_t^C and deposits with the Federal Reserve that represent the foreign repo pool, which it holds in quantity $\tilde{M}_t^C$. These assets back riyal reserves, M_t. The central bank manages its portfolio over these three assets and sets taxes to keep the exchange rate fixed, $e_t = \bar{e}$.

We assume that the oil-producing central bank sets its supply of riyal reserves according to the following rule:

$$M_t = \kappa M_t^0 + (1 - \kappa)\bar{M} \tag{5}$$

where M_t^0 is the level of riyal reserves consistent with equal returns on dollar and riyal deposits, and $\bar{M}$ is a fixed level of reserves that we assume represents the central bank's domestic policy target for managing inflation and unemployment.

In the first period, the central bank chooses its level of Treasury holdings and deposit holdings with the Fed. These choices carry through to the second period, where, with probability p, the central bank cannot sell Treasuries. In addition, the oil-exporting central bank has to worry about two shocks. The first is the change in net exports, which is realized in the morning. The second is that the central bank must meet international banks' demand for riyal loans in the afternoon.

[5] One objection to this assumption is that the U.S. market is large relative to the demands placed by the oil-exporting countries. We have two responses to that objection. First, our results persist in sign, if not in magnitude, if we allow for elasticity in the supply of and demand for Treasuries as long as neither is perfectly elastic. Second, our empirical results show that foreign central bank Treasury sales do appear to affect domestic deposit rates. As the evidence from March 2020 shows, such sales can be large relative to the amount of liquidity the U.S. money market provides.

[6] When demand is somewhat inelastic, the results are qualitatively similar, but the effects are smaller, except that Treasury yields also rise due to increases in net export volatility.

This demand, in the aggregate, is equal to S_t because the within-country shocks Z_t and $\tilde{Z}_t$ are mean zero. We assume that to meet this demand, the central bank cannot sell Treasuries but must instead rely on their holdings of deposits with the Federal Reserve. If those holdings are exhausted, as with the international banks, the foreign central bank faces a cost ψ above the rate on dollar reserves. This cost represents the discount the central bank must accept when selling other assets to raise dollars in the evening.

These assumptions imply a budget constraint for the central bank in the morning of the first and second periods:

$$\bar{e}B_2^C + \bar{e}\tilde{M}_2^C = \tau_2 + M_2 + \bar{e}\left(y_1 + \tilde{\delta}_1\tilde{M}_1^C\right) - \delta_1 M_1 + c\,\mathrm{E}\left[L_1\right],$$

which includes the profits on central bank assets from the previous period and from lending to banks at a penalty rate in the first period.

To maintain the fixed exchange rate target, the central bank must balance the current account and financial account. Adding up all domestic balance sheet constraints in the second period requires that:

$$\mathrm{NX}_2 = \bar{e}\left(B_2^C - y_1B_1^C + \tilde{M}_2^C - \tilde{\delta}_1\tilde{M}_1^C\right) - M_2 + \delta_1 M_1 - \bar{D} + r_1 D \tag{6}$$

The requirement of a fixed exchange rate pins down taxes by the central bank, which acts to hold marginal utilities of consumption between the United States and the oil producer constant. With deposits fixed by consumer demand, when net exports fall, the oil producer decreases its holdings of dollar assets or increases its supply of riyal reserves to balance the financial account balances with the current account at the fixed exchange rate.

Given the constraint imposed by net exports, the central bank maximizes its investment return while taking into account the cost of providing dollar-to-riyal foreign exchange liquidity. In period 2, if the Treasury market is liquid, the central bank solves:

$$\begin{aligned} V^U(Q_2) = \max_{B_2^C,\tilde{M}_2^C} \quad & y_2B_2^C + \tilde{\delta}_2M_2^C - \chi\int_{s=\tilde{M}_2^C}^{\infty} S - \tilde{M}_2^C\,dG(S) \\ \text{such that} \quad & \bar{e}\left(B_2^C + \tilde{M}_2^C\right) - M_2 = Q_2 + \tau_2, \end{aligned}$$

where Q_2 reflects the net worth of the foreign central bank at the beginning of period 2, including its holdings of Treasuries, deposits with the Fed, fees from lending to banks in the first period, and the foreign reserves held by banks. The value function in this state is independent of its choice of Treasuries. In the liquid market, Treasuries are fungible with the central bank's other investments.

If the Treasury market is illiquid, the central bank's holdings of Treasuries are fixed at B_2^F, so that the central bank's payoff is:

$$V^C(Q_2, B_2^F) = y_2 B_2^F + \tilde{\delta}_2(Q_2 + \tau_2 - M_2 - B_2^F) - \chi \int_{s=Q_2+\tau_2-M_2-B_2^F}^{\infty} S - Q_2 + \tau_2 - M_2 - B_2^F \, dG(S), \quad (7)$$

which reflects the central bank's budget constraint and inability to transact in Treasuries in an illiquid market. As a result of this constraint, the central bank's decision between Treasuries and reserves in period 1 matters in period 2.

In period 1, the central bank maximizes the expected value of their period 2 return, subject to period 1 net exports and net worth. We assume that there is no exchange shock at time zero, so that their relative expected return in period 2 determines the central bank's choice of Treasuries and deposits with the Fed. The central bank's objective at time 1 is therefore:

$$\begin{aligned}
\max_{M_1, B_1^C} \quad & \beta p \, \mathrm{E}\left[V^U(Q_2)\right] + \beta(1-p)\, \mathrm{E}\left[V^C(Q_2, B_2^F)\right] \\
\text{such that} \quad & \bar{e}\left(B_1^C + \tilde{M}_1^C\right) - M_1 = Q_1 + \tau_1 \\
& Q_2 = \bar{e}\left(y_1 B_1 + \tilde{\delta}_1 \tilde{M}_1^C\right) + c\, \mathrm{E}\left[L_1\right] - \delta_1 M_1 \\
& B_2^F = y_1 B_1^C + (\tilde{\delta}_1 - 1)\tilde{M}_1^C + (\delta_1 - 1) M_1 - (r_1 - 1) D_1,
\end{aligned}$$

where the last constraint reflects that in an illiquid market Treasuries tomorrow are fixed at the level held today plus interest income on other assets. The latter component of B_2^F simplifies the calculation of equilibrium without affecting the model's implications.

4.5 Model Implications

In the model's equilibrium, five markets clear: the market for riyal deposits, the market for riyal reserves, the market for dollar reserves, the market for dollar deposits, and the market for Treasuries. The net-exports shock, NX_2, determines the paths of each of these variables and is the main driving force of the model's dynamics. There are three financial factors, y_t (which reflects the cost of funds), $y_t - \tilde{\delta}_t$ (which reflects dollar liquidity), and $\delta_t - \tilde{\delta}_t$, which reflects riyal liquidity relative to dollars. Any asset in the model can be described by these factors. The two liquidity factors reflect the tightness of reserves in the United States and the oil-producing country.

These factors, in turn, reflect the settlement frictions that cause the demand for reserves to be segmented between the United States and the oil-producing country. In the United States, the deposit market friction means that:

$$y_t - \tilde{\delta}_t = cF(\theta \tilde{D} - \tilde{M}_t), \tag{8}$$

where F is the cumulative distribution function of the combined deposit shock to U.S. banks, $\tilde{Z}_t + S_t$. This condition equates the difference between the return on holding Treasuries and reserves to the expected cost of reserve shortfalls next period, reflecting the additional benefit reserves have in meeting this requirement.

Because U.S. dollars cannot be used to meet oil-producing country reserve requirements means that a different factor is necessary to represent the relative costs of liquidity in the oil-producing country:

$$\delta_t - \tilde{\delta}_t = cF(\theta \tilde{D} - \tilde{M}_t) - cF(\theta \bar{D} - M_t). \tag{9}$$

Given the pegged exchange rate, this equation describes the deviation from covered interest parity, which reflects intermediary settlement demand for reserves in each country. As the U.S. rate on reserves increases relative to that in the oil-producing country, the intermediary is willing to hold more U.S. deposits and fewer reserves. On the other hand, from the oil-producing central bank's point of view, if U.S. liquidity increases, to keep the exchange rates fixed, the central bank must either tolerate higher interest-rate differentials or supply more reserves domestically. Along with the central bank's commitment to keeping the current account balanced, this equation, in combination with the central bank's reserve setting equation, constrains the oil-producing central bank's decision resulting from the peg.

4.5.1 Equilibrium interest-rate differentials

Motivated by the stylized facts we dcoumented, we now discuss situations under which interest rate differentials will respond to a shift from Treasuries to deposits with the Federal Reserve by the oil producer's central bank. Its monetary policy target implies that:

$$M_t = \kappa\theta(\bar{D} - \tilde{D}) - \kappa\bar{A} + \kappa\tilde{M}_t^C + (1-\kappa)\bar{M}$$

If κ is close to one, the oil producer's central bank is willing to tolerate large changes in the supply of riyal reserves to match dollar interest rates. In this case, there is no response of interest rate differentials to changes in the central bank's holdings of deposits with the Federal Reserve. The central bank will undo the effect of its own actions by changing the supply of riyal reserves. But more generally, the central bank does not increase riyal reserves by enough to offset the increase in interest rate differentials fully. As a result, interest rate differentials widen. This effect is summarized in the following theorem, which we derive in Appendix B:

Theorem 1 *For $0 \leq \kappa < 1$, if the oil producer central bank's target level of riyal reserves is set such that in expectation interest rate differentials are zero, then an increase in their holdings of deposits with the Fed will lead to wider interest-rate differentials.*

This conclusion is a direct consequence of the central bank's commitment to keeping the exchange rate fixed and its desire to maintain a supply of riyal reserves for independent monetary policy purposes. The more the central bank is willing to tolerate changes in the supply of riyal reserves, the less interest rate differentials will widen in response to changes in the central bank's holdings of deposits with the Fed.

4.5.2 Precautionary liquidity demand by the foreign central bank

In this environment, the portfolio decisions of the oil-producing central bank matter for dollar and riyal liquidity. Following from Equation 6, in response to a decrease in net exports, the central bank must either sell Treasuries, decrease its holdings of deposits with the Fed, or increase its supply of riyal reserves. With a fixed supply of dollar reserves, if the oil producer chooses to respond by reducing its deposit holdings with the Fed, it leaves more dollar reserves for the intermediary, which increases U.S. liquidity and reduces domestic spreads. The greater supply of riyal reserves means spreads decline, but that decline may push the central bank away from its domestic monetary policy target. Meanwhile, Treasury sales by the oil-producing country reduce reserve holdings in the United States and the oil-producing country when the intermediary takes them on. The primary implications of the model are that the portfolio decisions by the foreign central bank, induced by shocks to net exports, affect U.S. liquidity.

We focus particularly on the response to net export volatility. If net export volatility increases, precautionary demand increases, and the oil producer's central bank demands more dollar liquidity. This demand reduces dollar liquidity to the intermediary and increases dollar funding spreads. We summarize this implication in the model's main theorem, which we explicitly derive in Appendix B:

Theorem 2 *For ψ sufficiently large, an increase in σ_X causes the oil exporter's central bank to sell Treasuries and hold more deposits with the Fed, leading to wider interest-rate differentials and dollar money market spreads as liquidity is drained from the U.S. market.*

This feature of the model results from the oil-producing central bank's precautionary demand for dollar liquidity. If the Treasury market is illiquid, the oil producer's central bank requires sufficient dollar deposits with the Fed going into the second period to cover its settlement risk. In this case, the central bank is unable to build sufficient dollar deposits by selling Treasuries. The precautionary motive produces the downward-sloping demand curve in Figure 7. As interest rates on dollar deposits fall relative to Treasuries, the central bank is more willing to face the possibility that it may not have sufficient dollar deposits tomorrow to meet the settlement shock.

Equilibrium occurs when the central banks' willingness to hold dollar deposits with the Fed equals the demand for reserves from the intermediary since both are splitting the Fed's fixed balance sheet. The upward-sloping blue line in Figure 7 represents the total size of the Fed's balance sheet less intermediary demand, which responds to the U.S. liquidity factor.

As net export volatility increases, the central bank faces greater precautionary demand for reserves. This effect is reflected in the darker shaded lines in Figure 7. Higher net export volatility in equilibrium increases the odds that the central bank is left with too few reserves to cover its needs for dollar deposits with the Fed for settlement balances. At the same time, U.S. liquidity decreases, as the oil-producing central bank holds more dollar deposits, which means that there are fewer reserves for the intermediary. As the central bank holds more deposits, it must sell Treasuries or issue more domestic reserves for the same level of net exports today. The more weight the oil exporter's central bank attaches to keeping the domestic interest rate at the target in its objective function, the more Treasuries it sells to the intermediary, and the fewer reserves it sells. However, unless the central bank places weight only on its interest rate target, the central bank will not increase reserves by enough to offset the increase in interest rate differentials fully. As a result, interest rate differentials will widen.

4.5.3 The effect of the FIMA repo facility

The model also shows how liquidity facilities such as FIMA repo facility mitigates the effects of the oil exporter's central bank's demand for dollar liquidity. The Federal Reserve introduced this facility on March 31, 2020, allowing foreign official accounts holding Treasuries with the Federal Reserve to borrow money through repo agreements with the Fed at a prearranged rate. A much broader set of countries became eligible for these facilities than the swap line facility, and its explicit goal was to provide temporary liquidity to Treasury holders.

In the model, the FIMA repo facility provides an alternative and lower cost way of meeting settlement demand for dollars for the oil producer's central bank. We assume that the facility occurs at the same penalty rate, c, as charged by the Federal Reserve for meeting settlement balances of international banks. This matches the current design of the FIMA facility, which offers the same rate as the Federal Reserve's Standing Repo Facility offers to primary dealers and certain banks. The FIMA facility, therefore, dominates the existing technology for securing settlement balances. The new precautionary demand thus reflects the lower expected cost of insufficient settlement balances. Specifically, the cost of shortfalls in settlement balances is now equal for international banks and the oil-producing country's central bank. Equating these two costs dramatically changes the equilibrium effects of net export shocks:

Theorem 3 *If the Federal Reserve supplies adequate reserves for international banks in expectation, then following the introduction of a FIMA facility with a penalty rate equal to c, (1) the oil producer's central bank reduces its holdings of deposits with the Federal Reserve, (2) the oil producer's central bank increases* *its Treasury holdings, (3) the oil producer's central bank no longer increases its holdings of deposits with the Federal Reserve when net exports increase.*

Although international banks and the oil-producing country's central bank now faces the same cost of shortfalls, the international banks face additional risk of shortfalls from the possibility that deposits are reallocated between banks in the same currency. As a result, the oil producer's central bank no longer holds positive deposits with the Federal Reserve in equilibrium. Instead, it holds more Treasuries.

This change is shown in Figure 8 by the shift from the intersection of the blue and red lines to the intersection of the blue and green lines. At the new equilibrium point, increases in volatility on the margin lead to greater holdings of reserves from the international banks rather than from the oil producer's central bank as a result of the shift in the marginal probability of a shortfall for each group. Therefore, the introduction of the FIMA repo facility incentivizes the foreign central bank to hold more Treasuries and release more U.S. liquidity to international banks, reducing the impact of a reserve shock. In fact, in the presence of the FIMA repo facility, as long as the Federal Reserve provides adequate reserves to meet demand from international banks, there is no longer a need to provide additional reserves to the oil producer's central bank. The facility eliminates the need for the Fed explicitly to consider foreign central bank demand when ensuring U.S. money markets are adequately liquid.

5 Empirical analysis

5.1 Identification strategy

For the countries in the sample, the model lays out a causal chain from oil market shocks that cause changes in oil price volatility to oil exporters' interest rate differentials, to Treasury sales that consume dollar liquidity. This chain provides a theoretical structure to the empirical relationships that motivate our analysis. That structure permits us to identify the effect of oil exporter's foreign exchange reserve management decisions on dollar liquidity.

This transparent and microfounded chain of causation allows us to credibly address the challenges of reverse causality in the relationship between exchange rates and dollar liquidity. In particular, Correa et al. (2020) shows that dollar illiquidity in the repo market can affect exchange rates by raising arbitrage costs. If borrowing costs in dollar repo markets rise, the returns to arbitrage between the dollar and the foreign currency reflect those higher costs. In this case, changes in repo market illiquidity unrelated to the effects of foreign reserve management decisions cause exchange rate fluctuations. For oil exporters, however, the model provides a direct channel that is not influenced by U.S. money market liquidity – these countries' central banks have an independent incentive to sell Treasuries in response to oil market shocks that affect oil price volatility. The model, therefore, suggests oil price volatility as a natural instrument for exchange rate management decisions by oil exporters.

However, the chain of causation laid out in the model does not, without additional assumptions, guarantee that the exclusion restriction holds. For example, the model does not account for the possibility that oil exporters may exercise market power through OPEC to set oil prices. The countries in the sample may also make a joint decision about oil production and managing their exchange rate pegs, undermining the credibility of the model's causal chain. Additionally, OPEC decisions could affect oil price volatility without influencing exchange rate management decisions if oil producers have private information about the likely effects of those decisions unavailable to other market participants.

Several pieces of evidence cast doubt on the validity of these claims and suggest that the exclusion restriction is likely satisfied. OPEC has historically been more effective at restricting new capacity growth rather than limiting production from existing wells (Smith, 2009). The relevant time horizons for developing new oil production capacity are months and years rather than days or weeks, making it implausible that OPEC decisions would affect the demand for dollar liquidity at the horizons we examine. Moreover, geological constraints are the primary determinants of an oil well's flow rate once the operator drilled it, leaving it largely outside operator control (Newell and Prest, 2019). Thus, the geology of oil production justifies the assumption our model's assumption of exogenous oil production over the horizons relevant for our analysis. Finally, Anderson et al. (2018) provide microeconomic evidence and theoretical results consistent with the idea that the price elasticity of oil supply is close to zero within the month.[7]

[7]Kilian (2022) surveys the econometric issues related to estimating demand and supply elasticities in the crude oil market, with a particular emphasis on structural VARs.

Furthermore, although oil producers possess an informational advantage in all aspects of their ability to change oil production and existing capacity, this advantage does not necessarily translate into superior information for oil pricing. Brunetti et al. (2013) show OPEC's so-called fair price pronouncements have little influence on the market price of crude oil. They provide little new information to oil futures market participants, calling into question the assumption that OPEC countries have superior information about oil pricing. The absence of an informational advantage makes it less probable that oil exporters can forecast the direction of oil prices and volatility, and manage their foreign exchange reserves in advance of those changes. In sum, the available evidence points to the validity of the premises of the identification strategy implied by the model.

To address remaining questions about possible confounding effects, we construct a daily dummy variable based on a series of OPEC supply announcements during the sample period by scraping press releases from the OPEC website. These announcement data are intended to control for information related to OPEC's plans for future production. We then introduce additional controls based on the realized Brent returns on the announcement dates. We include these variables as controls in the first and second stages of the instrumental variables regressions.

Although using oil price volatility provides a credible solution to the reverse causality problem, simultaneity remains a concern in the absence of additional controls. Oil price volatility can reflect market forces acting on oil, reserve management pressures, and Treasury markets at the same time. We face a similar challenge in how oil volatility affects the repo market through channels other than the one on which the model relies. For example, the revelation of U.S. macroeconomic news to market participants can create uncertainty about the current and future state of the economy, which likely contributes to high-frequency fluctuations in repo spreads and oil price volatility. Moreover, oil market shocks that drive option implied volatility can independently create uncertainty about the global macroeconomic outlook.

We deal with these challenges in two ways. First, although oil price changes have a clear link to global growth and, hence, oil demand news, option implied volatility in the price of oil has a less predictable relation with oil demand. Second, we control for several factors that independently affect repo rates and plausibly affect liquidity and oil price volatility at high frequencies (i.e., daily news). To ensure that changes in repo spreads and oil price volatility are not attributable to the release of U.S. macroeconomic news, we control for macro and financial news developments using the VIX.[8] Finally, we include a dummy variable for FOMC announcement dates that reveal news relevant to money markets and have implications for growth. We also include Brent returns to separate general changes in oil prices from volatility. At the daily frequency, the specification with these additional controls purges the instrument of these confounding forces, enabling us to identify the channel implied by the model.

5.2 Repo data

We collect daily data on repo rates from Refinitiv to test the model's implications. Figure 9 presents the different interest rates we use to measure repo and money market activity and the transactions to which they apply. The aggregate measures of repo rates include the Secured Overnight Funding Rate (SOFR) and the General Collateral Finance (GCF) repo index. SOFR is a broad measure of repo funding rates that the Federal Reserve Bank of New York maintains. GCF measures inter-dealer general collateral repo rates from the Fixed Income and Clearing Corporation's (FICC) cleared tri-party GCF repo service.

We examine the spread of these repo rates relative to several baseline interest rates. The spread of SOFR over the interest rate on excess reserves (IOER) is a broad measure of the difference between repo rates and rates that banks receive for holding excess reserves with the Federal Reserve. Next, the difference between the GCF index and the IOER provides a narrower picture on the behavior of inter-dealer spreads. Another spread that measures the difference between inter-dealer funding costs and the costs to dealers of borrowing from institutions such as small banks and money market funds is the difference between the GCF repo rate and the Tri-party General Collateral rate (TGCR). Finally, the spread between the GCF rate and the effective Federal Funds rate (EFFR) measures the difference between secured inter-dealer rates and the overnight rate banks borrow unsecured from institutions such as the Federal Home Loan Banks. Table 9 reports summary statistics for these repo spreads over the sample period.

[8] In unreported results, we find that including the U.S. daily economic policy uncertainty from Baker, Bloom, and Davis (2016) leaves the main conclusions of our empirical results materially unchanged.

5.3 Data on other controls

Repo rate spreads respond to several factors that influence the supply of and demand for liquidity (Correa et al., 2020; Afonso et al., 2020; and Anbil et al., 2021). Accordingly, we include controls for the determinants of repo spreads, including daily Treasury issuances of notes, bonds, and bills from TreasuryDirect, volumes in the Treasury General Account (TGA) from daily Treasury statements, Federal Reserve purchases of Treasury securities, and volumes in the overnight reverse-repurchase and repo facility. We also include three-month Treasury bill yields from FRED. Finally, we construct a dummy variable to capture month-end funding pressure related to foreign banks' incentives to window dress their positions (Munyan, 2015; and Anbil and Senyuz, 2018) and corporate income tax payment data that measure withdrawals from money market funds.

In unreported results, we also estimate the baseline regressions controlling for three-month CIP deviations of G10 countries relative to the United States, and the results are broadly unchanged. The results of these regressions allay the concern that our main findings reflect the intermediary funding constraints rather than the responses of central banks to terms of trade shocks (Du et al., 2023).[9]

Our empirical analysis proceeds in two stages. First, we project the interest rate factor onto option implied oil price volatility and the controls:

$$IR_t = \alpha + \gamma OIV_t + \Gamma \mathbf{X}_t + \nu_t, \tag{10}$$

where IR_t is the interest rate factor, OIV_t is option implied Brent price volatility, and $\mathbf{X}_t$ is a vector of variables including the oil market controls described in subsection 5.1, controls related to Treasury markets described in subsection 5.3, and the VIX.

The first set of specifications tests the model's main implication – that dollar liquidity demand from foreign central banks exerts a meaningful influence on the cost of US liquidity. Thus, our first

[9]The only case where the results differ from the baseline regression results is in diminished statistical significance for some of the narrow money market spreads in the 2015 to 2020 sample. These results differ from the baseline not in magnitude or sign, but due to inflation in the standard errors, suggesting that adding three-month CIP deviations introduces substantial noise. A reason why the estimated coefficients become noisier is that we had to obtain the three-month cross-currency basis swaps, the economically relevant tenor, from several different pricing sources.

set of second-stage results projects the various repo spreads on the fitted IR factor, $\widehat{IR}_t = \hat{\gamma} OIV_t$.

$$S_t = \alpha + \rho S_{t-1} + \beta \widehat{IR}_t + \Psi \mathbf{X}_t + \epsilon_t \tag{11}$$

Given the unprecedented nature of the COVID-19 shock in March 2020 and the resulting dash for cash, the baseline regression controls include a dummy equal to one in the last two weeks of March 2020. All regression results are reported with and without this indicator variable. For ease of interpretation, we standardize the fitted IR factor to have zero mean and unit variance.

5.4 Repo spread results

We start with the results from daily regressions of repo spreads on implied interest rate differentials instrumented by oil option-implied volatility in Table 10 and Table 11. Table 10 reports the results from the first-stage regressions and Table 11 the second-stage regression results.

The sample sizes differ across the regressions because the reference rates from the Federal Reserve, specifically the SOFR and TGCR, are available only after 2014, while the GCF index begins in 2005. As Table 10 shows, despite the different sample periods, the first stage is remarkably consistent. The results for the SOFR-IOER and GCF-TGCR spreads in columns 1 - 2 and 5 - 6 rely on estimates from the short sample. The results for the GCF-IOER and GCF-EFFR spreads in columns 3 - 4 and 7 - 8 rely on estimates from the longer sample.

This specification explains a substantial share of the daily variation of the IR factor in the first stage – around 50%. As Figure 6 shows, oil price volatility exhibits a close relationship with the implied interest-rate differentials, and it is highly statistically significant after including other controls in the regressions. Implied interest-rate differentials also comove with TGA balance and counter to the Treasury bill yield SOMA net purchases. However, the amount of variability in the implied interest-rate differentials that these three variables account for is small. In the longer samples, the VIX and Brent returns are inversely correlated with the IR factor. The instrument is strong for both sample periods, with F-statistics over 170.

Table 11, which reports the second-stage results from daily regressions of repo spreads on implied interest rate differentials using oil option implied volatility as the instrument. In addition to the controls described above, these regressions include a lagged dependent variable, as the spreads tend to be reasonably stable day-to-day.

The first four columns report the impact of the fitted interest rate factor on broad repo market spreads, which represent the difference between the repo rates and the unsecured rates banks receive from the Federal Reserve. A one-standard deviation increase in interest rate differentials leads to an almost three basis point increase in the SOFR over IOER and about a 2.4 basis point increase in GCF over IOER, which is the closest equivalent to the spread between intermediary funding rates and policy rates in the model.

We compare these estimated responses to the summary statistics in Table 9 to put them into perspective. The spread between the 25th and 75th percentile of the SOFR-IOER and GCF-IOER spreads is roughly fifteen basis points, meaning that the increases are large relative to the daily history of these rates. For additional perspective, a 2.85 (2.41) basis point increase in the SOFR-IOER (GCF-IOER) spread would fall above the 75th percentile of the unconditional distribution of spreads' daily changes.

The economic interpretation of these results is related to the meaning of the spreads over IOER. These spreads measure the difference in funding rates between banks, which can invest at the IOER, and non-banks, such as money-market funds, which cannot. Thus, this evidence highlights the importance of reserve scarcity and market segmentation in transmitting oil market shocks to oil exporters' exchange rates and, ultimately, repo markets.

Columns 5 - 8 provide further information on determinants of repo spreads using liquidity measures that affect the dealers and banks that borrow from certain non-banks. Let us start with the results in columns 7 and 8. The GCF-EFFR spread represents the market rate at which banks borrow from specific non-bank institutions such as Federal Home Loan Banks, as Afonso et al. (2013) points out. The results in columns 7 - 8 show that a one standard deviation increase in interest rate differentials leads to a roughly 2.1 basis point increase in the GCF-EFFR spread. These results indicate that much of the total estimated GCF-IOER response (2.4 basis points) is attributable to the demand for unsecured funds beyond what the IOER captures.

The GCF-TGCR spread provides another measure of repo market spreads, and the second-stage regression results based on them are in columns 5 - 6. This spread compares two overnight rates secured by Treasuries: the inter-dealer cleared tri-party GCF rate and the customer-to-dealer uncleared tri-party rate. Both are for general collateral Treasury transactions. The TGCR represents the rate at which money market funds lend to dealers, and GCF is the rate at which dealers borrow and lend to each other in the repo market. A one standard deviation increase in the implied interest rate differential leads to a 0.72 basis point increase in this spread. Although the estimated coefficient is not universally statistically significant, it carries the anticipated sign and becomes statistically significant when we include the March 2020 dummy.

In Table 12, we present the results of OLS regressions of repo spreads on the implied interest rate differential factor. Compared with the estimates from the IV regressions in Table 11, the signs and magnitudes of the estimated coefficients of all the factors other than the implied interest rate differential factor are similar across the two specifications. By contrast, the pattern of signs of the estimated coefficients associated with the implied interest rate differential factor are more consistent in the IV regressions. They also line up with the model's prediction that oil volatility-driven shock to the factor causes an increase in U.S. repo market spreads. The magnitudes of the estimated coefficients in the IV regressions are also larger than those in the OLS regressions. This comparison suggests that using option-implied oil price volatility as an instrument credibly alleviates the endogeneity and simultaneity problems in empirical tests linking the demand for dollar liquidity by oil exporters' central banks and U.S. money market spreads.

5.4.1 Subsample Analysis

We conduct two tests to examine whether the main results are sensitive to anomalies in different subsamples. First, we include baseline results with and without a dummy for the March 2020 dash for cash. The signs and magnitudes of the estimated coefficients remain largely the same between specifications, as shown in the columns in Table 11.

Second, in Table 13, we restrict the sample to start in 2015, following the SEC's money market reforms when funding conditions were generally tighter. The results do not change materially except that the magnitudes of the estimated coefficients associated with the SOFR-IOER, GCF-IOER, and GCF-EFFR spreads all increase. Moreover, the larger standard errors render the result for the GCF-EFFR spreads insignificant. Scarcer reserves and structural changes in money markets in 2015 may be the causes of this change.

5.5 Validating the model-implied channel

Next, we examine the channel through which oil exporters' interest rate differentials affect U.S. money markets and whether it aligns with the economic logic we develop in the model. So far, the regression results indicate a plausibly causal relationship between exchange rate fluctuations and repo market spreads. However, they do not directly shed light on whether oil volatility-driven shocks in the implied interest rate differentials of oil exporters spill over to U.S. short-term funding markets through the specific channel implied by the model – by oil exporters' central banks decreasing their Treasury holdings, which increases dealers' Treasury holdings and reduces reserves available to fund those Treasury holdings.

We examine the relationship between implied interest rate differentials and oil exporters' Treasury holdings to test this idea. The specification in these regressions is nearly identical to that in Equation 11, except that taking the first difference of TIC holdings obviates the need for the lagged dependent variable. Table 14 displays the regression results using the monthly TIC data, reducing the number of observations available in the estimation. The first two columns correspond to the data in Figure 6. The results in those columns suggest that oil-exporting countries' holdings decrease by roughly \$2 billion in response to a one standard deviation increase in the fitted IR factor. This evidence is consistent with the model's logic: the oil exporters sell Treasuries to defend their exchange rate pegs in response to terms of trade shocks. Columns 3 - 6 show that almost all the sales consist of long-term Treasuries, which decrease by a statistically significant \$1.7 billion. These changes represent around 0.31 standard deviations, which puts them in the bottom 25% of the unconditional distribution. By contrast, there is no significant impact on short-term Treasuries. This result is also consistent with the model's predictions: oil exporters' central banks sell less liquid Treasuries because they need the more liquid ones to conduct reserve operations.

The second set of columns in Table 14 focuses on all holdings by foreign official accounts. Although the total Treasury holdings for oil exporters mix foreign official accounts for the exporters and private holdings, the foreign official holdings data mix holdings by oil exporters and other countries but reflect exclusively foreign central banks and other government funds. The overall effect on short- and long-term Treasury holdings is insignificant, suggesting that the impact on Treasury sales is concentrated in oil-producing countries. The results are unchanged when we include a dummy for March 2020.

We extend the analysis by examining the effects of implied interest rate differential shocks on U.S. financial institutions and various accounts with the Federal Reserve. Based on the model, we hypothesize that foreign Treasury sales decrease reserves as the cash held in the foreign repo pool increases. Table 15 reports the regression evidence for these effects by examining the impact on primary dealers and Federal Reserve accounts. We use weekly data on the foreign repo pool balances and swap lines from the Federal Reserve Board's H.4.1. Factors Affecting Reserve Balances release. These accounts are subject to slow-moving trends unrelated to the mechanism we are concerned with, so we account for these trends by including a lagged dependent variable, as in Equation 11.

The first two columns in Table 15 show that a one standard deviation increase in implied interest rate differentials of oil exporters is associated with a \$1.2 - \$1.5 billion increase in the foreign repo pool. This estimate is similar in magnitude to the monthly decrease from foreign official accounts in Table 14 and indicates that oil exporters' foreign exchange management decisions reduce the supply of reserves to the rest of the financial system. The foreign repo pool investments lead to lower reserves with banks, assuming the same level of assets held at the Federal Reserve. Investing in the foreign repo pool is a highly liquid investment for foreign central banks, corresponding to the option to invest in reserves that the oil exporter's central bank has in the model.

Another way for certain central banks to obtain dollars is through swap lines with the Federal Reserve. Fleming and Klagge (2010), Allen et al. (2017), Cetorelli et al. (2020), Eguren-Martin (2020), and Aizenman et al. (2022), among others, have examined the effects of these swap lines. Based on this evidence, columns 3 and 4 of Table 15 look at the response of the swap facility to an oil volatility shock to implied interest rate differentials. Our preferred specification in column 4 suggests no statistically significant effect, which has a straightforward interpretation: the swap lines are only available to a select group of large, developed countries. Following the COVID-19 crisis, the Fed extended the swap lines to Australia, Brazil, Korea, Mexico, Singapore, Sweden, Denmark, Norway, and New Zealand but not to any of the oil exporters in our sample. Therefore, the results in this column serve as a placebo test and indicate that shocks to oil exporters' implied interest rate differentials do not lead to the rebalancing of reserve positions by developed non-oil exporters.[10]

Taken together, these results provide evidence for the primary mechanism developed in the model. Shocks to exchange rate management by major oil exporters lead to (1) decreases in these countries' holdings of long-term Treasuries; (2) decreases in foreign official holdings of Treasuries; and (3) decreases in the supply of reserves to dealers as foreign central banks invest the proceeds in the foreign repo pool. These findings support the central claims of our argument – that exchange rate management decisions by foreign central banks remove liquidity from U.S. markets, leading to higher short-term funding costs.

6 Conclusion

We develop a model that shows how foreign reserve management decisions can adversely affect U.S. money market liquidity. This creates a natural concern for the Federal Reserve in maintaining dollar liquidity for foreign central banks. The model also provides a credible way to identify the effect of foreign central bank demand for dollar liquidity on repo spreads. Foreign official sector demand for dollar liquidity can have substantial effects on U.S. money market liquidity because foreign official investors drain reserves from the system at the same time that the money markets have to absorb large sales of Treasury securities, with commensurately broad implications for U.S. banks, dealers, and the supply of reserves. The empirical evidence indicates that the effect of foreign official demand for dollar liquidity on spreads in short-term funding markets are economically and statistically significant. A one-standard deviation increase in central bank demand for dollar liquidity in an oil-exporting country leads to a two to three basis point increase in U.S. money market spreads and, on average, Treasury sales of $2 billion.

A way to mitigate this adverse effect on U.S. money market liquidity follows naturally from the model – for the Federal Reserve to adopt a broad view of liquidity provision in a future dash for cash. In a banking system with ample reserves, foreign official sales of Treasuries have a more limited effect on domestic money market liquidity. However, during much of the sample

[10]Here, the inclusion of the March 2020 dummy makes an important difference in the results. The statistically significant relationship between the fitted IR factor and swap line usage in column 3 is driven entirely by the two largest jumps in the time series. In the last two weeks of March 2020, swap line use jumped 17 and then another 12 standard deviations over the sample average. For context, the third largest increase was four standard deviations in December of 2011. This reflects the unprecedented market conditions surrounding the emergence of the COVID -19 pandemic, which reinforces the importance of examining a longer sample.

period, reserves were scarce, and foreign official accounts were one of several sources of demand for access to the Federal Reserve's balance sheet. Given the dollar's use by many developed and emerging market reserve managers, the amount of reserves must be sufficient to accommodate the diverse needs of those market participants. These needs extend well beyond the large economies with access to the swap lines and beyond traditional large holders of Treasuries such as China and Japan. Our findings underscore the importance of liquidity facilities such as the Foreign and International Monetary Authorities (FIMA) Repo Facility as an effective way to reduce stress in global dollar funding markets and prevent adverse spillovers from abroad to U.S. short-term funding markets.

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A Assumptions on consumer preferences

This Appendix outlines assumptions that are sufficient for the starting point of the two-period model that:

1. Deposits are fixed.

2. Net exports are an exogenous function of taste shocks.

3. Taste shocks are positively correlated with oil prices.

These assumptions are not key to the mechanism we highlight in the rest of the paper, but they help to provide a general equilibrium framework for our results.

The oil exporter's household obtains utility from consumption, C_t, oil, X_t, and a non-tradable good N_t. It has an endowment of oil wells, W, that produces a quantity of oil W each period and sells it at a globally determined price v_t. The assumption of a constant oil supply matches the frequency of our empirical analysis, which is daily or weekly. Over those horizons, the oil supply is likely to be fixed. The exporter's household also has an endowment of the non-tradable good, H.

Consumers discount at a rate β and maximize the discounted present value of their utility:

$$\sum_{t=0}^{\infty} \beta^t \,\mathrm{E}\left[\frac{1}{1+\omega_t}\log(C_t) + \frac{\omega_t}{1+\omega_t}\log(X_t) + \gamma\log(N_t)\right], \tag{12}$$

where ω_t represents a shock to oil demand that we postulate is exogenous and use to generate changes in oil prices and the current account. The budget constraint is:

$$p_t C_t + v_t X_t + D_t + \tau_t + N_t = v_t W + H + r_{t-1} D_{t-1}, \tag{13}$$

where p_t is the price of consumption, v_t is the globally determined oil price, D_t are domestic deposits, τ_t is lump-sum taxes, and r_t is the gross return on those deposits.

We also assume that consumers face a deposits-in-advance constraint:

$$p_t C_t + v_t X_t \leq r_{t-1} D_{t-1}$$

This construction simplifies deposit demand, allowing us to obtain an equilibrium in financial markets.

The U.S. household is nearly symmetric in terms of preferences, except that it also demands Treasuries:

$$\sum_{t=0}^{\infty} \beta^t \,\mathrm{E}\left[\frac{1}{1+\omega_t}\log(\tilde{C}_t) + \frac{\omega_t}{1+\omega_t}\log(\tilde{X}_t) + \gamma\log(\tilde{N}_t) + \rho\log(\tilde{B}_t)\right] \tag{14}$$

The U.S. household is subject to the same preference shock of oil, ω_t, as the oil exporter's household. The U.S. consumer's demand for Treasuries represents a dimension of liquidity not captured in the intermediaries' decision problem or as a reduced-form way to create preferred habitat demand.

The U.S. household also faces a different budget constraint represented in terms of the oil exporter's currency:

$$p_t \tilde{C}_t + v_t \tilde{X}_t + e_t \tilde{D}_t + \tilde{\tau}_t + e_t \tilde{N}_t + e_t \tilde{B}_t = p_t Y + e_t \tilde{H} + \tilde{r}_{t-1} e_t \tilde{D}_{t-1} + e_t y_t \tilde{B}_{t-1} + \int_0^1 \pi_{t-1}(i)di,$$

where e_t is the exchange rate, Y is a consumption endowment, $\pi_{t-1}(i)$ represents the profit of intermediary i, and tildes denote U.S. values. The assumption that the United States owns the consumption endowment simplifies the model, and the prices of oil and the consumption good reflect the law-of-one price. As with the oil-exporting consumer, the U.S. consumer is subject to a deposit-in-advance constraint $p_t\tilde{C}_t + v_t\tilde{X}_t e_t r_{t-1} \leq \tilde{r}_{t-1} e_t \tilde{D}_{t-1}$.

We assume a fixed endowment of the non-tradable good, $H = \tilde{H} = \frac{1}{\gamma}$, which pins down each household's marginal utility of consumption. The assumption of a deposit-in-advance constraint simplifies the problem, and with logarithmic utility, it leads to a fixed demand for deposits:

$$D_t = \bar{D} \qquad \tilde{D}_t = \tilde{D},$$

whenever r_t and $\mathrm{E}\left[e_{t+1}\right] e_t^{-1} r_t$ are less than β^{-1}. This assumption simplifies analyzing the effect of oil demand shocks. With deposit demand and the exchange rate fixed, the oil exporter's central bank must balance payments by buying or selling U.S. assets, consistent with standard economic intuition. But assuming that consumers' deposit demand is responsive to interest rates would not materially change the model's conclusions.

Meanwhile, the household's logarithmic utility combined with the deposit constraint imply that:

$$\begin{aligned} p_t C_t &= \frac{1}{(1+\omega_t)} r_{t-1}\bar{D} & \qquad v_t X_t &= \frac{\omega_t}{(1+\omega_t)} r_{t-1}\bar{D} \\ p_t\tilde{C}_t &= \frac{1}{(1+\omega_t)} e_t\tilde{r}_{t-1}\tilde{D} & \qquad v_t\tilde{X}_t &= \frac{\omega_t}{(1+\omega_t)} e_t\tilde{r}_{t-1}\tilde{D}, \end{aligned}$$

which leads to a straightforward expression for net exports:

$$\mathrm{NX}_t(\omega) = \frac{\omega_t}{(1+\omega_t)} e_{t-1}\tilde{r}_{t-1}\tilde{D} + \left(1 - \frac{\omega_t}{(1+\omega_t)}\right) r_{t-1}\bar{D} \tag{15}$$

As ω_t increases, the U.S. consumer demands a higher share of oil in the consumption bundle, and the consumer in the oil-exporting country demands a lower share, leading to an increase in net exports. At the same time, the price of oil rises as global demand increases. These conditions lay out the basic mechanisms necessary for the rest of the model.

B Proofs of theorems in the text

B.1 Proof of Theorem 1

We can derive the expected difference in interest rate differentials as a function of the foreign central bank's holdings of deposits with the Fed. It is given by:

$$\delta_t - \tilde{\delta}_t = cF\left(\theta\tilde{D} - \bar{A} + \tilde{M}_2^C\right) - cF\left((1-\kappa)\theta\bar{D} + \kappa\theta\tilde{D} - \kappa\bar{A} + \kappa\tilde{M}_2^C + (1-\kappa)\bar{M}\right), \tag{16}$$

where we have simply substituted foor M_2 using the oil producing country central bank's rule. We then differentiate this expression with respect to $\tilde{M}_2$ to get:

$$\frac{\partial(\delta_t - \tilde{\delta}_t)}{\partial\tilde{M}_2} = cf(\theta\tilde{D} - \bar{A} + \tilde{M}_2^C) - c\kappa f\left((1-\kappa)\theta\bar{D} + \kappa\theta\tilde{D} - \kappa\bar{A} + \kappa\tilde{M}_2^C + (1-\kappa)\bar{M}\right).$$

This term is positive whenever κ is sufficently small. Moreover, if interest rates are equalized between the two countries ex-ante, then $\theta\tilde{D} - \bar{A} + \tilde{M}_2^C = (1-\kappa)\theta\bar{D} + \kappa\theta\tilde{D} - \kappa A + \kappa\tilde{M}_2^C + (1-\kappa)\bar{M}$, in which case this derivative is positive for any $\kappa < 1$.

B.2 Proof of Theorem 2

As more the foreign central bank holds more deposits with the Fed, it is necessarily the case that the foreign central bank holds fewer Treasuries. Similarly, liquidity is necessarily drained from the U.S. since reserves of intermediaries are equal to $\bar{A} - \tilde{M}_1^C$. Finally, U.S. money market spreads are increasing in $\tilde{M}_1^C$ since from the intermediaries' first-order condition:

$$\tilde{r}_1 - \tilde{\delta}_1 = c(1-\theta)F(\theta\tilde{D} - \bar{A} + \tilde{M}_1^C).$$

Therefore, it is sufficient to show that equilbrium $\tilde{M}_2^C$ is increasing in σ_X.

First, in an illiquid market, applying the central bank's constraint for B_2 to equation 6 yields:

$$\mathrm{NX}_2 = (\tilde{M}_2^C - \tilde{M}_1^C) - (M_2 - M_1),$$

which says that if the central bank cannot use Treasuries to meet the net export shock, it uses deposits with the Fed or adjusts its own reserve supply. Meanwhile, substituting in the central bank's target for domestic reserves and reorganizing yields:

$$\tilde{M}_2^C = \tilde{M}_1^C + \frac{1}{1+\kappa}\mathrm{NX}_2.$$

Turning to the central bank's reserve allocation problem in period 2, in a liquid market where the oil producing central bank can choose optimal holdings of Treasuries, marginal returns on Treasuries and deposits with the Fed for the foreign central bank equalsy_2. In a constrained market, while marginal returns on Treasuries will be equal to y_2, marginal returns on deposits with the Fed will be:

$$\mathrm{E}\left[\tilde{\delta}_2\right] + \psi\left[1 - G\left(\tilde{M}_2^C\right)\right],$$

where G is the CDF of S_2.

Next, we turn to the decision to invest in Treasuries or deposits with the Fed in period 1. A dollar invested in deposits with the Fed in period 1 yields one dollar of deposits with the Fed period 2 and $\delta_1 - 1$ dollars of Treasuries in period 2. Therefore, indifference between Treasuries and dollar deposits today implies:

$$y_2 y_1 = (1-p)y_2\delta_1 + p\left(y_2\delta_1 + \mathrm{E}\left[\tilde{\delta}_2 - y_2\right] + \psi\,\mathrm{E}\left[1 - G\left(\tilde{M}_1^C + \frac{1}{1+\kappa}\mathrm{NX}_2\right)\right]\right)$$
$$y_2(y_1 - \delta_1) = p\left(\mathrm{E}\left[\tilde{\delta}_2 - y_2\right] + \psi\,\mathrm{E}\left[1 - G\left(\tilde{M}_1^C + \frac{1}{1+\kappa}\mathrm{NX}_2\right)\right]\right).$$

Substituting in from the first-order conditions of the international intermediaries, this equation becomes:

$$cy_2F(\theta\bar{D} - \bar{A} + \tilde{M}_1^C) = p\left(\psi\,\mathrm{E}\left[1 - G\left(\tilde{M}_1^C + \frac{1}{1+\kappa}\mathrm{NX}_t\right)\right] - c\,\mathrm{E}\left[F\left(\theta\bar{D} - \bar{A} + \tilde{M}_1^C + \frac{1}{1+\kappa}\mathrm{NX}_t\right)\right]\right). \tag{17}$$

The left-hand side of this equation is monotonically increasing, with aymptotes at 0 and cy_2, while the right hand side is monotonically decreasing with a maximum of $p\psi$ and a minimum of $-pc$. The equilbrium of the model therefore always exists and is unique.

Since NX_2 is normally distributed, we can rewrite both expectations using the underlying normal distributions, by combining the net export shock with the deposit shocks:

$$\mathrm{E}\left[F\left(\theta\bar{D}-\bar{A}+\tilde{M}_1^C+\frac{1}{1+\kappa}\mathrm{NX}_2\right)\right]=\mathrm{P}\left(\tilde{Z}_t+S_t-\frac{1}{1+\kappa}\mathrm{NX}_2<\theta\tilde{D}-\bar{A}+\tilde{M}_1^C\right)$$
$$=\Phi\left(\frac{\theta\tilde{D}-\bar{A}+\tilde{M}_1^C}{\sqrt{\sigma_Z+\sigma_S+(1+\kappa)^{-1}\sigma_X}}\right),$$

where Φ is the standard normal CDF. Applying this method to all three shocks yields:

$$cy_2\Phi\left(\frac{\theta\tilde{D}-\bar{A}+\tilde{M}_1^C}{\sqrt{\sigma_Z^2+\sigma_S^2}}\right)=p\left[\psi\Phi\left(-\frac{\tilde{M}_1^C}{\sqrt{\sigma_S^2+(1+\kappa)^{-2}\sigma_X^2}}\right)-c\Phi\left(\frac{\theta\tilde{D}-\bar{A}+\tilde{M}_1^C}{\sqrt{\sigma_Z^2+\sigma_S^2+(1+\kappa)^{-2}\sigma_X^2}}\right)\right]. \tag{18}$$

This equation describes equilbrium in the model.

Examining the equilibrium determination in Equation B.2, the equation's left-hand side is unaffected by an increase in σ_X. Therefore, for $\tilde{M}_1^C$ to increase in σ_X, the derivative of the right-hand side must be positive to shift equilbrium out and to the right. The derivative of the right-hand side with respect to σ_X^2 is:

$$\frac{\partial\mathrm{RHS}}{\partial\tilde{\sigma}_X^2}=\frac{p}{2(1+\kappa)^2}\left[\frac{\psi\tilde{M}_1^C}{\left(\sigma_S^2+(1+\kappa)^{-2}\sigma_X^2\right)^{3/2}}\times\phi\left(\frac{\tilde{M}_1^C}{\sqrt{\sigma_S^2+(1+\kappa)^{-2}\sigma_X^2}}\right)\right. \tag{19}$$
$$\left.+\frac{c(\theta\bar{D}-\bar{A}+\tilde{M}_1^C)}{\left(\sigma_Z^2+\sigma_S^2+(1+\kappa)^2\sigma_X^2\right)^{3/2}}\times\phi\left(\frac{\theta\bar{D}-\bar{A}+\tilde{M}_1^C}{\sqrt{\sigma_Z^2+\sigma_S^2+(1+\kappa)^{-2}\sigma_X^2}}\right)\right].$$

A sufficient condition for the derivative to be positive is that $\tilde{M}_1^C > \min\{0,\tilde{D}-\bar{A}\}$. Further, this derivative is increasing in ψ for $\tilde{M}_1^C > 0$. When $\tilde{M}_1^C > \min\{0,\tilde{D}-\bar{A}\}$, the derivative also generally decreases as κ approaches zero – that is, the less flexible domestic demand for liquidity is, the larger the effect on U.S. liquidity will be.

For the theorem to be true, it is sufficient that for $\psi^\star$ high enough, equilibrium will occur to the right of $T=\min\{0,\tilde{D}-\bar{A}\}$, or in other words that for $\psi^\star$ high enough:

$$p\psi^\star\Phi\left(-\frac{T}{\sqrt{\sigma_S^2+(1+\kappa)^{-2}\sigma_X^2}}\right)-pc\Phi\left(\frac{\theta\tilde{D}-\bar{A}+T}{\sqrt{\sigma_Z^2+\sigma_S^2+(1+\kappa)^{-2}\sigma_X^2}}\right)-cy_2\Phi\left(\frac{\theta\tilde{D}-\bar{A}+\tilde{T}}{\sqrt{\sigma_Z^2+\sigma_S^2}}\right)>0.$$

This requirement is clearly possible. As long as $\psi>\psi^\star$, an increase in σ_X leads to an increase in $\tilde{M}_1^C$, and the rest of the theorem follows.

B.3 Proof of Theorem 3

If $\psi=c$ and $\theta\tilde{D}-\bar{A}=0$, then at $\tilde{M}_1^C=0$, the right-hand side of Equation (B.2) this equation would be 0. Meanwhile, the left-hand side would be >0. Therefore, the equilibrium occurs when $\tilde{M}_1^C<0$.

Further, if $\psi = c$ and $\theta\tilde{D} - \bar{A} = 0$, then Equation 19 becomes:

$$\frac{\partial \text{RHS}}{\partial \tilde{\sigma}_X^2} = \frac{pc\tilde{M}_1^C}{2(1+\kappa)^2}\left[\frac{1}{\left(\sigma_S^2 + (1+\kappa)^{-2}\sigma_X^2\right)^{3/2}} \times \phi\left(\frac{\tilde{M}_1^C}{\sqrt{\sigma_S^2 + (1+\kappa)^{-2}\sigma_X^2}}\right)\right.$$
$$\left. + \frac{1}{\left(\sigma_Z^2 + \sigma_S^2 + (1+\kappa)^2\sigma_X^2\right)^{3/2}} \times \phi\left(\frac{\tilde{M}_1^C}{\sqrt{\sigma_Z^2 + \sigma_S^2 + (1+\kappa)^{-2}\sigma_X^2}}\right)\right].$$

This derivative is always ≤ 0 when $\tilde{M}_1^C \leq 0$. Therefore, when $c = \psi$, increases in σ_X do not cause increases in $\tilde{M}_1^C$.

C Data Description

Here, we describe the data used in the analysis.

1. **SOFR-IOER**: Secured overnight financing rate (SOFR) minus the interest rate on excess reserves (IOER). SOFR is from the Federal Reserve Bank of New York's reference rates API, and the IOER data come from FRED.

2. **GCF-IOER**: General collateral finance (GCF) Treasury repo index minus the interest rate on excess reserves (IOER). The GCF repo index is from the Fixed Income Clearing Corporation's website, and the IOER data comes from FRED.

3. **GCF-TGCR**: General collateral finance (GCF) Treasury repo index minus the Treasury general collateral rate (TGCR). The GCF repo index is from the Fixed Income Clearing Corporation's website, and the TGCR data come from the Federal Reserve Bank of New York's reference rates API.

4. **GCF-EFFR**: General collateral finance (GCF) Treasury repo index minus the effective federal funds rate (EFFR). The GCF repo index is from the Fixed Income Clearing Corporation's website, and the EFFR data come from the Federal Reserve Bank of New York's reference rates API.

5. **Total Treasury sales (Oil exporter / All foreign official)**:

6. **Long-term Treasury sales (Oil exporter / All foreign official)**:

7. **Short-term Treasury sales (Oil exporter / All foreign official)**:

8. **Foreign repo pool volumes**: Volumes in the foreign official repo pool, from Federal Reserve H.4.1. *Factors Affecting Reserve Balances* release, under the line "Reverse repurchase agreements: Foreign official and international accounts", obtained from FRED.

9. **Swap line volumes**: Volumes in swap lines, from Federal Reserve H.4.1. *Factors Affecting Reserve Balances* release, under the line "Central bank liquidity swaps", obtained from FRED.

10. **Oil price volatility**: Implied volatility of options on at-the-money Brent oil, obtained via Eikon (RIC LCOc1O=R).

11. **IR factor**: The interest-rate (IR) factor is the first principal component of interest rate differentials for the sample countries. Exchange rate information is obtained from Eikon. We use the three-month forward and spot rates for Bahrain (RIC BHD=, BHD3M=), Oman (RIC OMR=, OMR3M=), Qatar (RIC QAR, QAR3M=), Saudi Arabia (RIC SAR=, SAR3M=), United Arab Emirates (RIC AED=, AED3M=).

12. **Coupon/bill issuance**: Obtained by aggregating issuance of coupon securities/bills from issuance data scraped from TreasuryDirect.gov.

13. **TGA balances**: Obtained from Daily Treasury Statements data from fiscaldata.treasury.gov, under the table "Operating Cash Balance," series "Treasury General Account Opening Balance."

14. **Income tax payment**: Obtained from Daily Treasury Statements data from fiscaldata.treasury.gov, under the table "Federal Tax Deposits," series "Corporation Income Taxes."

15. **SOMA net purchases**: Obtained by aggregating purchases of Treasury coupon securities from the Federal Reserve Bank of New York's Markets API for Treasury Securities Operations.

16. **Brent return**: Daily return to first-to-deliver Brent futures, obtained from Eikon (RIC LCOc1=R).

17. **OPEC Announcment**: Realized return to Brent futures on OPEC announcement days. The OPEC announcement days are obtained by scraping all Press Releases on the OPEC website, https://www.opec.org/opec_web/en/press_room/28.htm, and using the dates of each announcement. Brent returns are obtained as above.

18. **VIX**: CBOE Volatility Index, obtained from FRED.

Figure 1: **Treasury sales in March 2020.** Sales are the difference between positions at the end of February and the end of March for total Treasuries using the TIC major foreign holders of Treasuries data.

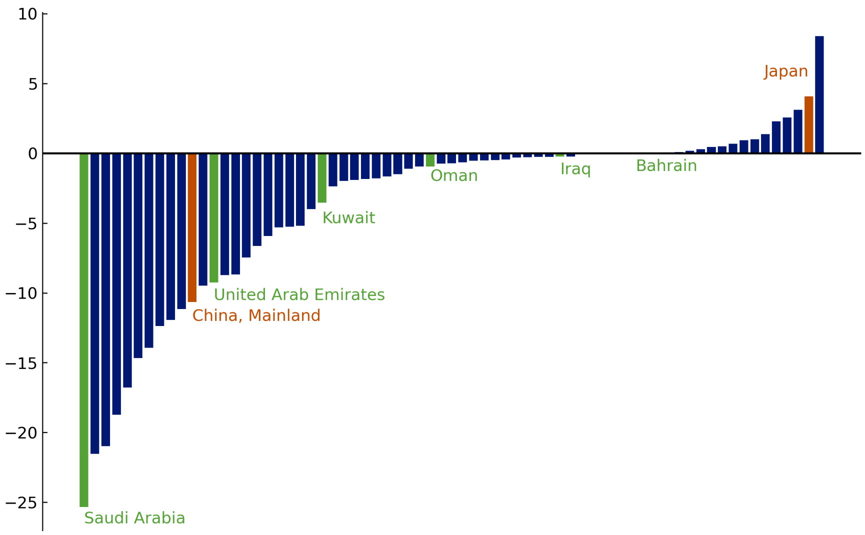

Figure 2: **Foreign official sales and repo rates during March.** Sales (in blue) are weekly changes in foreign custody holdings with the Federal Reserve Bank of New York. The SOFR-IOER spread (in green) is the spread on the SOFR index over the interest rate on excess reserves, a measure of repo market illiquidity.

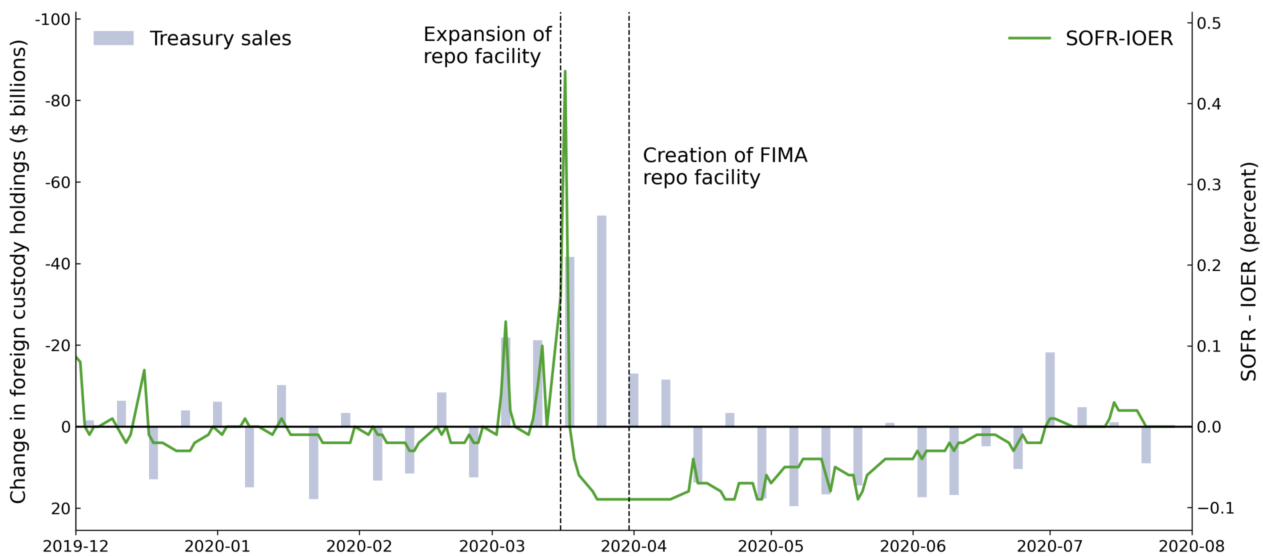

Figure 3: **Foreign official sales, foreign repo pool, and swap lines during March.** Foreign official Treasury sales (in blue) and foreign repo pool (in green) are measured relevative to their levels on February 26, 2020. On March 19, 2020, the Fed announced a major expansion of the swap lines (in dark blue) to nine additional central banks, all of which had access to Federal Reserve liquidity during 2007-09.

Figure 4: **Diagram depicting domestic mutual funds sales and foreign central banks sales.** Arrows denote the flow of cash or securities. The top panel examines the effects of sales by mutual funds. The bottom panel examines the effects of sales by foreign central banks that invest in the foreign repo pool. In the top panel, funds from the sale are available to the primary dealer through banks. In the bottom panel, funds enter the foreign repo pool and are therefore unavailable to the dealer.

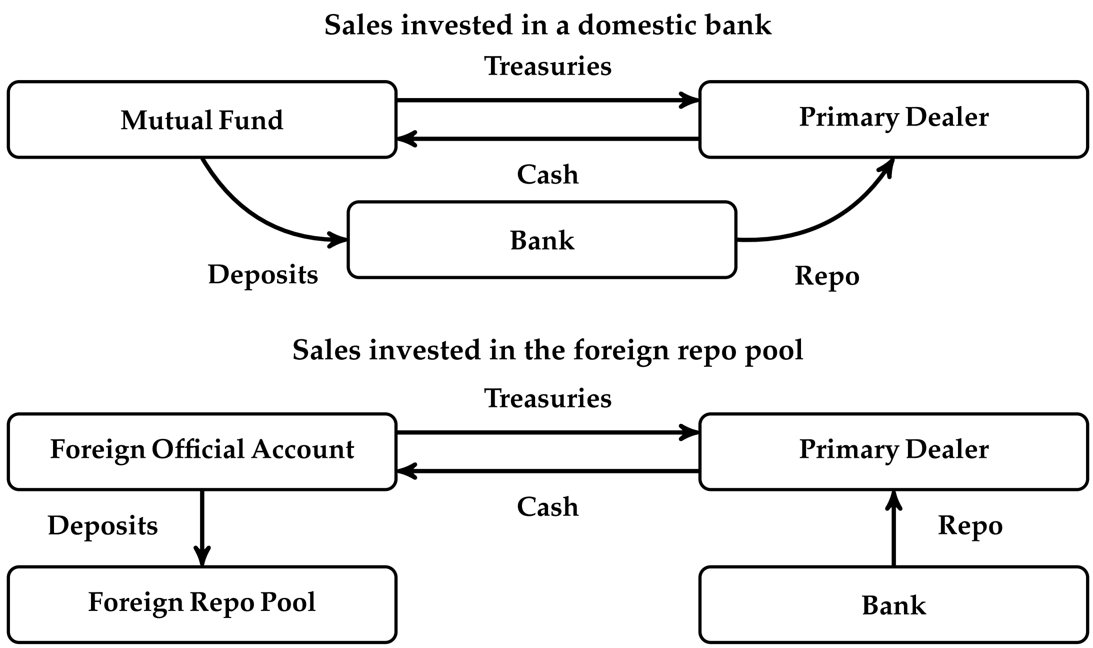

Figure 5: **Implied interest rate differentials across sample countries.** Daily implied differentials from forward and spot exchange rates

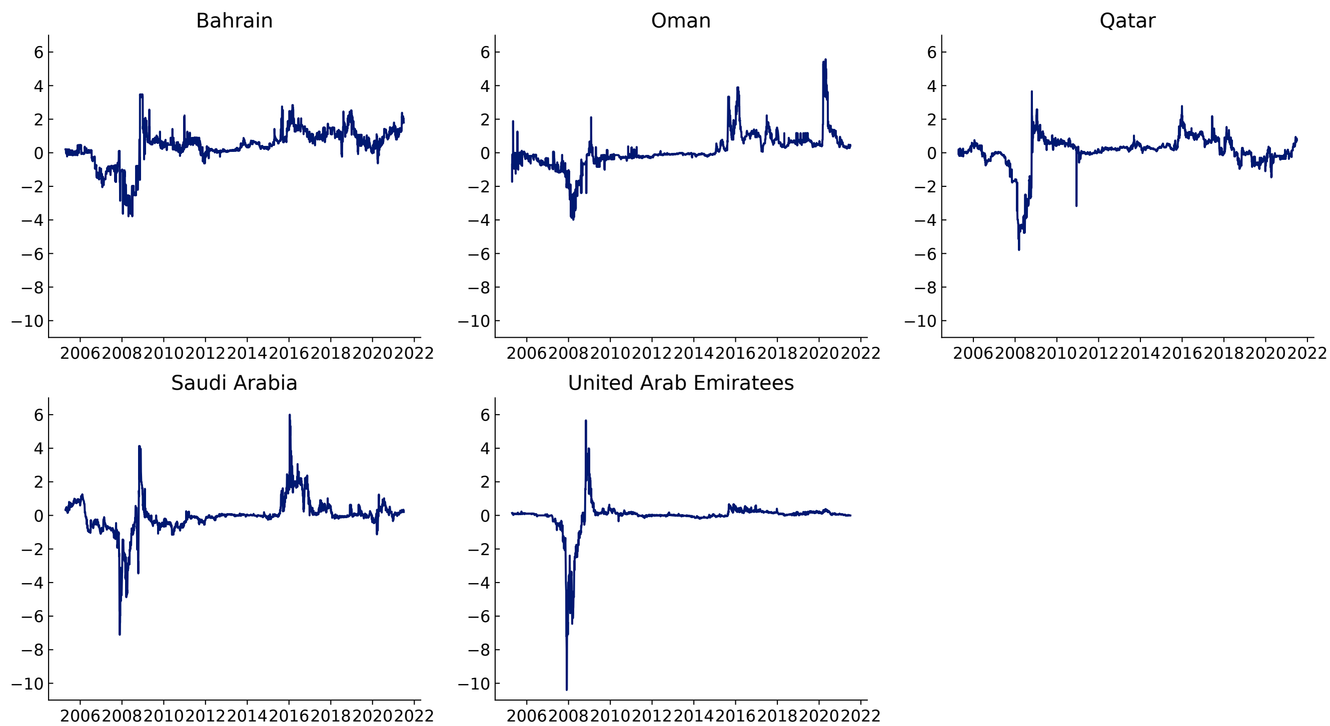

Figure 6: **Implied interest rate differentials, oil volatility and Treasury sales.** This figure shows daily data on Brent option-implied volatility from at-the-money options, along with daily data on interest rate differentials implied by exchange rate spot and forward swap prices and monthly data on Treasury sales imputed from changes in TIC holdings of our five sample major oil exporters with exchange rates pegged to the U.S. dollar. All series have been standardized so that they are mean zero and variance one in the sample.

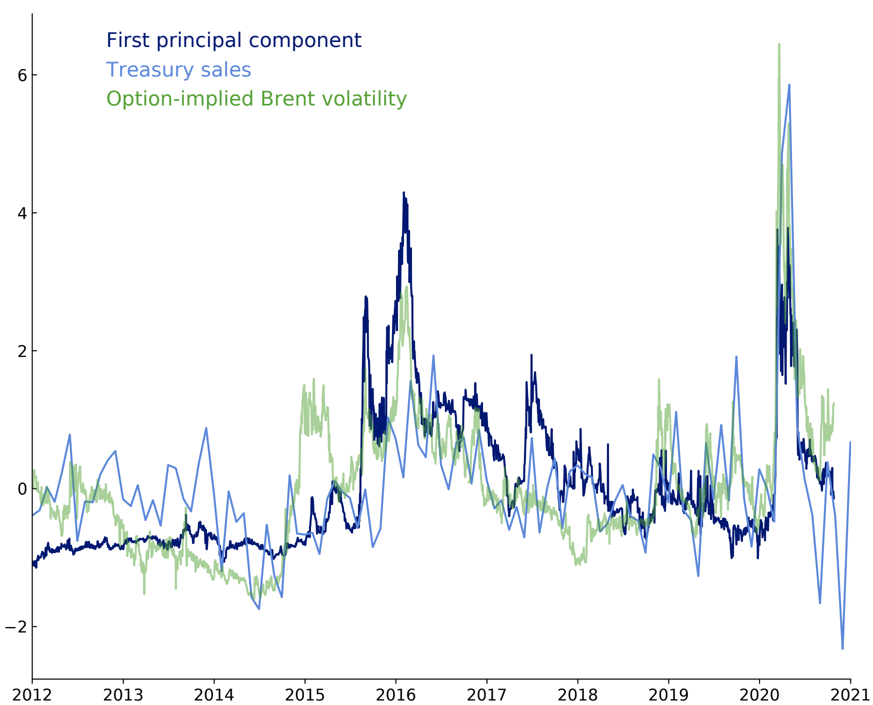

Figure 7: **Equilibrium in the model economy in period 1:** Equilibrium in the model occurs at the intersection of the red line, describing the return on U.S. liquidity for the foreign central bank, and the blue line describing the return on U.S. liquidity for the intermediaries. Darker red lines denote an increase in σ_X, the variance of the net exports shock.

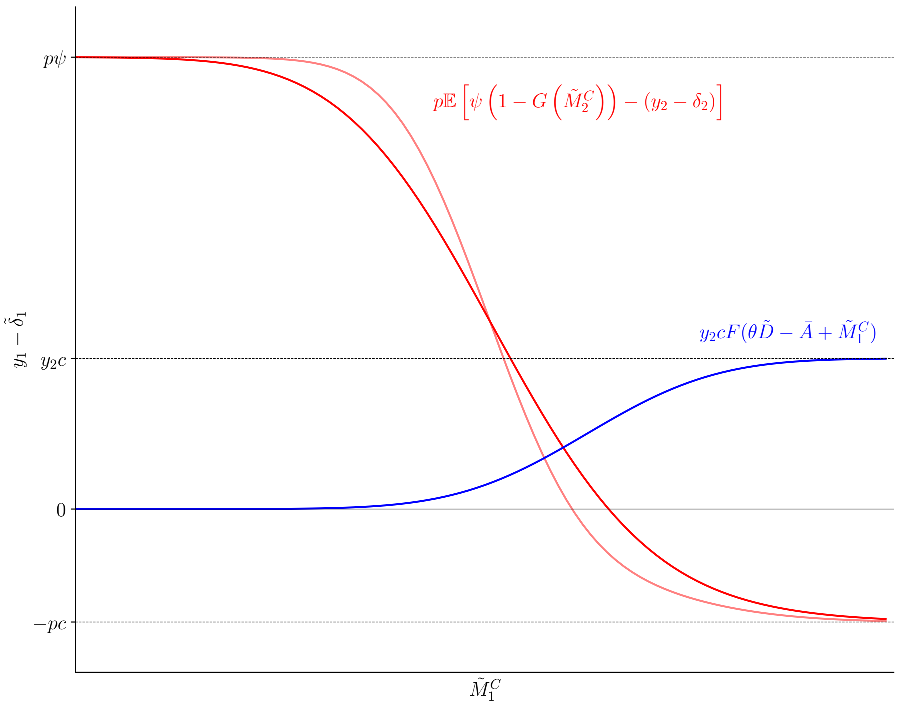

Figure 8: **Introduction of the FIMA repo facility in the model economy:** The preliminary equilibrium in the model occurs at the intersection of the red line, describing the return on U.S. liquidity for the foreign central bank, and the blue line describing the return on U.S. liquidity for the intermediaries. Darker red lines denote an increase in σ_X, the variance of the net exports shock. With the introduction of the FIMA repo facility, the cost of insufficient settlement balances is reduced, and equilibrium occurs at the intersection of the green and blue lines. Demand for deposits with the Fed decreases and spreads fall. Moreover, increases in the volatility of net exports lead to smaller increases in deposit demand and U.S. illiquidity.

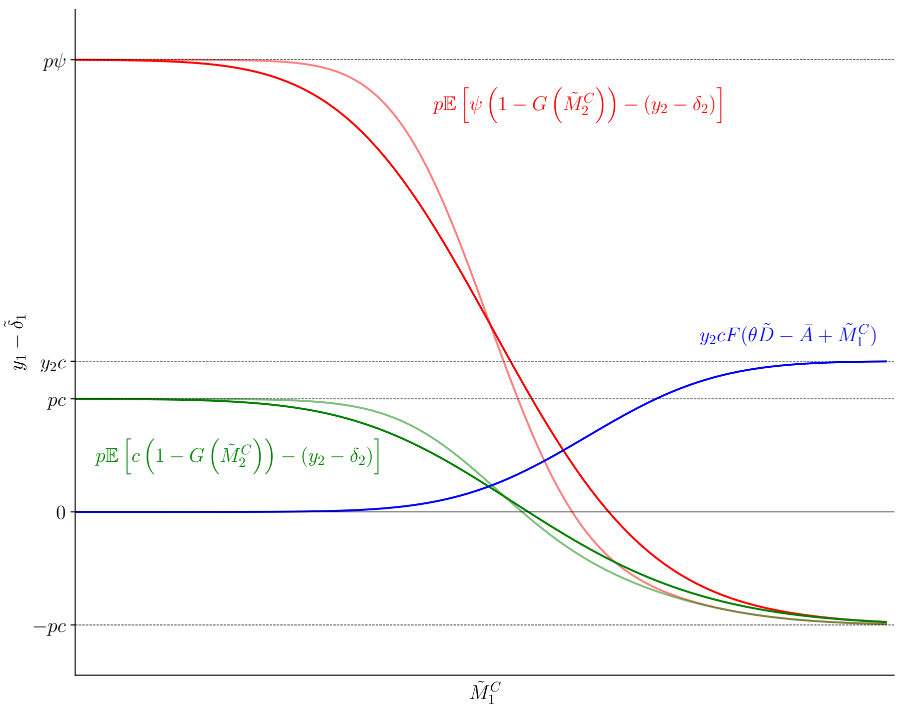

Figure 9: **Diagram of money markets and money market rate aggregates.** Arrows denote the flow of cash from cash lenders to cash borrowers. Dashed lines denote unsecured funding, while solid lines denote secured funding. For secured funding, securities flow in the opposite direction of the solid lines. Colored boxes denote the ranges of transaction each rate employed in this paper covers.

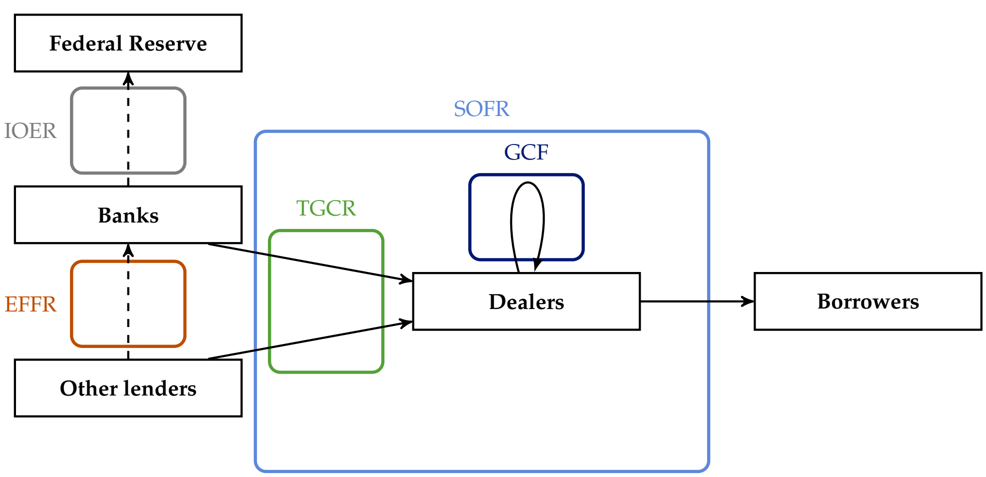

Table 1: **Total Treasury sales by group.** This table shows total sales, long-term Treasury sales, and short-term Treasury sales by country groups from the TIC holdings table in March 2020. Amounts are in billions of dollars. High oil production countries are in the top third of the TIC sample for oil production per capita (after removing countries without oil production). Hedge-fund domiciles are Bermuda, the British Virgin Islands, the Cayman Islands, Ireland, and Luxembourg. East Asian countries are China, Hong Kong, Macau, South Korea, Taiwan, Thailand, and Vietnam.

		Treasury sales	
	Total	Long-term	Short-term
High oil production	109.331	102.220	7.286
East Asia	34.699	50.244	-15.205
Hedge fund domiciles	46.956	59.977	-13.021
Foreign official accounts	147.052	124.194	22.858
All countries	260.719	251.780	8.939

Table 2: **Long-term Treasury sales in March 2020 by oil production per capita.** This table shows sales of long-term Treasuries from the TIC holdings table in March 2020. Amounts are in billions of dollars. The first column reports the number of countries, the second total sales of long-term Treasuries, and the third the average sales of long-term Treasuries. The fourth column reports controlled average sales, which are coefficients from a regression of total sales on GDP, a dummy for hedge-fund domiciles (Bermuda, British Virgin Islands, Cayman Islands, Ireland, and Luxembourg), and a dummy for East Asia countries (China, Hong-Kong, Macau, South Korea, Taiwan, Thailand, and Vietnam), and a dummy for the group they fall under for oil production per capita, where the omitted category is no oil production.

		Long-term Treasury sales			
Oil production per capita	**Countries**	Total sales	Average sales	Average sales (controlled)	t-stat
No oil production	22	80.024	3.637	-	-
Low	27	33.921	1.256	-0.160	-0.109
Middle	26	36.287	1.396	0.412	0.273
High	26	102.220	3.932	3.140	2.049

Table 3: **Countries in the Treasury International Capital System data with dollar pegs.** This table lists all countries in the TIC data that have dollar pegs as identified by the IMF's 2020 Annual Report on Exchange Arrangements and Exchange Restrictions. Countries classified as major oil exporters and countries with active futures markets are noted.

TIC countries with dollar peg	Oil exporters	Oil exporters with active futures market
Aruba		
The Bahamas		
Bahrain	✓	✓
Barbados		
Belize		
Curacao		
Iraq	✓	
Oman	✓	✓
Qatar	✓	✓
Saudi Arabia	✓	✓
United Arab Emirates	✓	✓

Table 4: **Summary statistics for the sample of oil countries with pegged exchange rates.** All quantities are normalized by GDP.

	Country				
	Bahrain	**Oman**	**Qatar**	**Saudi Arabia**	**UAE**
Exports	0.47	0.51	0.41	0.33	0.92
Imports	0.34	0.31	0.17	0.64	0.64
Net Exports	0.13	0.20	0.25	0.15	0.29
Government Debt	0.83	0.61	0.62	0.18	0.27
External Debt	≈ 2	0.94	1.38	0.23	0.82
Currency Reserves	0.10	0.22	0.21	0.63	0.25

Table 5: **Exchange rate peg and actual daily exchange rate distribution by country.** Data for the exchange rate distribution are from Refinitiv Eikon from November 1990 to October 2020.

		Empirical percentile						
	Peg	Min	0.10	0.25	0.50	0.75	0.90	Max
Bahrain	**0.377**	0.188	0.377	0.377	0.377	0.377	0.377	0.382
Oman	**0.384**	0.384	0.385	0.385	0.385	0.385	0.385	0.388
Qatar	**3.640**	3.614	3.640	3.640	3.641	3.641	3.642	3.864
Saudi Arabia	**3.750**	3.705	3.750	3.750	3.750	3.751	3.751	3.770
United Arab Emirates	**3.672**	3.656	3.673	3.673	3.673	3.673	3.673	3.704

Table 6: **Daily implied interest rate differential distribution by country.** Data for the exchange rates and forward exchange swap rates are from Refinitiv Eikon for April 2005 to July 2021. Interest rate differentials are annualized and reported in percentage points. The top panel includes all years while the bottom panel excludes 2007-2009 and Q1-Q2 of 2020.

	Empirical percentile (all years)						
	Min	0.10	0.25	0.50	0.75	0.90	Max
Bahrain	-1.273	-0.286	0.037	0.164	0.328	0.504	1.167
Oman	-3.721	-0.681	-0.260	-0.068	0.581	1.091	5.193
Qatar	-4.344	-0.464	-0.071	0.165	0.412	0.725	2.746
Saudi Arabia	-3.348	-0.373	-0.165	-0.011	0.107	0.421	2.826
United Arab Emirates	-7.101	-0.103	-0.011	0.044	0.120	0.191	3.866

	Empirical percentile (excluding crises)						
	Min	0.10	0.25	0.50	0.75	0.90	Max
Bahrain	-0.531	0.000	0.058	0.191	0.371	0.504	0.955
Oman	-1.611	-0.275	-0.156	-0.014	0.623	1.091	3.637
Qatar	-2.380	-0.218	-0.026	0.181	0.401	0.687	2.088
Saudi Arabia	-0.544	-0.219	-0.053	0.003	0.129	0.453	2.826
United Arab Emirates	-0.240	-0.038	-0.005	0.044	0.109	0.169	0.457

Table 7: **Correlation of implied interest rate differentials across countries.** Implied interest differentials are calculated on a daily basis from spot exchange rates and three-month forward swap agreements from 2005 to 2021. This table presents the correlations among these interest rate differentials for the five countries.

	Bahrain	**Oman**	**Qatar**	**Saudi Arabia**	**UAE**
Bahrain	1.00	0.65	0.69	0.65	0.56
Oman		1.00	0.50	0.62	0.47
Qatar			1.00	0.65	0.66
Saudi Arabia				1.00	0.73
UAE					1.00

Table 8: **Implied interest rate differentials and oil price volatility.** Implied interest differentials are calculated on a daily basis from spot exchange rates and three-month forward swap agreements from 2005 to 2021. Oil price volatility is calculated from at-the-money options on Brent futures. The first column presents the correlations between interest rate differentials and our factor based on the first principal component. The second column presents the correlation between interest rates and Brent oil volatility. The final two columns present the coefficient and standard error from regressions of each currency's implied interest rate differential (in basis points) on oil volatility from 2012 to 2021. All columns use daily data.

	Correlations		**Regression on oil volatility**	
	Principal component	Brent volatility	Coefficient	Standard error
Bahrain	0.800	0.212	0.451	(0.036)
Oman	0.864	0.305	5.730	(0.098)
Qatar	0.824	0.119	0.212	(0.077)
Saudi Arabia	0.839	0.265	1.299	(0.058)
UAE	0.791	0.259	0.513	(0.016)
Principal component	1.000	0.289	4.549	(0.096)

Table 9: **Summary statistics for repo rate spreads.** This table presents summary statistics for the various repo rate spread measures used in this paper from August 2014 to November 2020 on a daily basis.

	SOFR-IOER	GCF-IOER	GCF-TGCR	GCF-EFFR
Mean	-0.084	-0.014	0.101	0.054
Standard deviation	0.136	0.170	0.083	0.148
Minimum	-0.290	-0.302	-0.058	-0.212
25%	-0.170	-0.099	0.064	0.011
50%	-0.100	-0.012	0.087	0.049
75%	-0.010	0.046	0.124	0.087
Max	3.150	3.907	2.199	3.707

Table 10: **First stage of instrumental variables regressions for repo spreads.**

	Spread Measure							
	(1) SOFR-IOER	(2) SOFR-IOER	(3) GCF-IOER	(4) GCF-IOER	(5) GCF-TGCR	(6) GCF-TGCR	(7) GCF-EFFR	(8) GCF-EFFR
Oil price volatility	0.062***	0.062***	0.059***	0.058***	0.052***	0.052***	0.058***	0.056***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Coupon issuance	-0.001	-0.001	-0.001*	-0.001**	-0.001	-0.001	-0.001*	-0.001**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Bill issuance	-0.001	-0.000	-0.001	0.000	0.001	0.001	-0.001	0.000
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
T-bill yield	-0.001	-0.001	-0.001***	-0.001***	-0.002***	-0.002***	-0.002***	-0.002***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
TGA balances	0.001***	0.001***	0.003***	0.003***	0.001***	0.001***	0.003***	0.003***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Month-end dummy	0.031	0.029	0.037	0.039	0.095	0.093	0.045	0.047
	(0.12)	(0.12)	(0.07)	(0.07)	(0.11)	(0.11)	(0.07)	(0.07)
Income tax payment	0.000	0.000	0.002	0.002	-0.001	-0.001	0.002	0.002
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
SOMA net purchases	-0.022***	-0.033***	0.002	-0.021***	-0.014***	-0.018**	0.002	-0.020***
	(0.01)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)
OPEC Announcement	0.374	0.327	-0.233	-0.259	1.249	1.222	-0.151	-0.171
	(1.41)	(1.33)	(3.20)	(1.68)	(1.81)	(1.73)	(3.19)	(1.73)
Brent return	-0.266	-0.019	-1.518**	-0.898	0.176	0.278	-1.436**	-0.828
	(0.67)	(0.67)	(0.69)	(0.62)	(0.61)	(0.61)	(0.67)	(0.62)
FOMC announcement	-0.029	-0.044	-0.058	-0.088*	-0.086	-0.092	-0.068	-0.098*
	(0.08)	(0.08)	(0.05)	(0.05)	(0.09)	(0.09)	(0.05)	(0.05)
VIX	0.004	0.003	-0.042***	-0.044***	0.002	0.002	-0.042***	-0.045***
	(0.01)	(0.01)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
March 2020		0.903*		2.456***		0.379		2.392***
		(0.49)		(0.46)		(0.51)		(0.44)
IV F-stat	197.0	197.8	366.7	348.6	172.9	173.2	364.1	344.7
Observations	1340	1340	2441	2441	1340	1340	2441	2441
R^2	0.50	0.50	0.53	0.54	0.50	0.50	0.52	0.54

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 10 summarizes the first stage of daily instrumental variables regressions of repo spreads on z-scores of our implied interest rate differential measure (instrumented for by oil option-implied volatility) and a vector of controls, including an AR(1) term. Coupon issuance includes bonds and notes. Spreads are expressed in basis points. Robust standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 11: **Instrumental variables regressions for repo spreads.**

	Spread Measure							
	(1) SOFR-IOER	(2) SOFR-IOER	(3) GCF-IOER	(4) GCF-IOER	(5) GCF-TGCR	(6) GCF-TGCR	(7) GCF-EFFR	(8) GCF-EFFR
IR factor	2.85*	2.85*	2.41**	2.43**	0.72	0.73*	2.08**	2.14**
	(1.46)	(1.46)	(0.95)	(0.99)	(0.45)	(0.43)	(0.84)	(0.89)
Coupon issuance	0.03***	0.03***	0.05***	0.05***	0.03**	0.03**	0.04***	0.04***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Bill issuance	-0.05***	-0.05***	-0.03***	-0.03***	-0.04**	-0.03**	-0.03**	-0.03***
	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
T-bill yield	0.06***	0.06***	0.04***	0.04***	0.00	-0.00	0.02***	0.02***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.00)	(0.00)	(0.01)	(0.01)
TGA balances	-0.00	-0.00	-0.01*	-0.01*	-0.00	-0.00	-0.01	-0.01
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.01)
Month-end dummy	5.77***	5.77***	4.67***	4.67***	4.07***	4.06***	8.44***	8.43***
	(1.32)	(1.32)	(1.15)	(1.15)	(1.30)	(1.30)	(1.26)	(1.26)
Income tax payment	0.07**	0.07*	0.08**	0.08**	0.05	0.05	0.09***	0.09***
	(0.04)	(0.04)	(0.04)	(0.04)	(0.03)	(0.03)	(0.03)	(0.03)
SOMA net purchases	-0.09*	-0.08	-0.07**	-0.05	-0.05*	-0.07	-0.13***	-0.09
	(0.05)	(0.11)	(0.04)	(0.08)	(0.03)	(0.10)	(0.05)	(0.08)
OPEC Announcement	-37.12*	-37.06*	-106.15	-106.11	-97.45*	-97.57*	-92.54*	-92.49*
	(19.61)	(19.94)	(66.65)	(68.47)	(59.20)	(58.43)	(52.10)	(55.45)
Brent return	-3.15	-3.47	5.49	4.90	6.59	7.04	5.84	4.69
	(11.20)	(12.05)	(9.71)	(10.46)	(4.26)	(5.42)	(9.60)	(10.18)
FOMC announcement	1.90	1.91	1.41	1.44	0.14	0.11	1.23	1.30
	(3.09)	(3.15)	(2.06)	(2.11)	(0.66)	(0.64)	(2.05)	(2.10)
VIX	0.14	0.14	0.12*	0.12*	-0.01	-0.01	0.08*	0.09**
	(0.13)	(0.12)	(0.07)	(0.06)	(0.06)	(0.05)	(0.04)	(0.04)
March 2020		-1.17		-2.50		1.68		-4.84
		(7.39)		(8.35)		(7.74)		(7.44)
IV F-stat	197.0	197.8	367.1	349.1	173.1	173.4	364.5	345.2
Observations	1339	1339	2439	2439	1338	1338	2439	2439
R^2	0.45	0.45	0.56	0.56	0.58	0.58	0.34	0.34

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 11 summarizes the results of daily instrumental variables regressions of repo spreads (in basis points) on the z-score our implied interest rate differential measure (instrumented for by oil option-implied volatility) and a vector of controls, along with an AR(1) term. Coupon issuance includes bonds and notes. Robust standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 12: **OLS regressions for repo spreads.**

	Spread Measure							
	(1) SOFR-IOER	(2) SOFR-IOER	(3) GCF-IOER	(4) GCF-IOER	(5) GCF-TGCR	(6) GCF-TGCR	(7) GCF-EFFR	(8) GCF-EFFR
IR factor	-1.04***	-1.05***	0.07	0.01	0.70***	0.70***	0.27	0.26
	(0.32)	(0.33)	(0.20)	(0.17)	(0.18)	(0.19)	(0.24)	(0.22)
Coupon issuance	0.03***	0.03***	0.05***	0.05***	0.03**	0.03**	0.03***	0.03***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Bill issuance	-0.05***	-0.05***	-0.03***	-0.03***	-0.04**	-0.03**	-0.03**	-0.03***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
T-bill yield	0.04***	0.04***	0.03**	0.03**	-0.00	-0.00	0.01***	0.01***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)
TGA balances	0.01***	0.01***	0.00	0.00	-0.00	-0.00	0.00	0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Month-end dummy	5.57***	5.56***	4.64***	4.64***	4.07***	4.06***	8.43***	8.43***
	(1.31)	(1.31)	(1.15)	(1.15)	(1.30)	(1.31)	(1.29)	(1.29)
Income tax payment	0.07**	0.07**	0.08**	0.08**	0.05	0.05	0.09***	0.09***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
SOMA net purchases	-0.14***	-0.17	-0.06**	-0.11	-0.05*	-0.07	-0.12**	-0.13*
	(0.05)	(0.10)	(0.03)	(0.08)	(0.02)	(0.10)	(0.05)	(0.07)
OPEC Announcement	-28.59	-28.73	-103.02	-103.15	-97.71*	-97.84*	-90.95	-90.98*
	(17.94)	(17.55)	(70.80)	(67.22)	(59.04)	(58.31)	(55.46)	(54.77)
Brent return	2.29	2.94	5.73	6.97	6.56	7.02	6.07	6.34
	(9.40)	(10.07)	(9.38)	(9.88)	(4.06)	(5.12)	(9.35)	(9.50)
FOMC announcement	1.89	1.86	1.19	1.13	0.14	0.11	1.06	1.04
	(3.07)	(3.12)	(2.01)	(2.04)	(0.66)	(0.63)	(1.97)	(1.98)
VIX	0.31**	0.31***	0.12*	0.11*	-0.01	-0.01	0.08*	0.08**
	(0.12)	(0.12)	(0.07)	(0.06)	(0.05)	(0.04)	(0.04)	(0.04)
March 2020		2.33		5.27		1.69		1.12
		(6.93)		(7.56)		(7.73)		(6.01)
Observations	1344	1344	2444	2444	1343	1343	2444	2444
R^2	0.50	0.50	0.58	0.58	0.58	0.58	0.36	0.36

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 12 summarizes the results of daily OLS regressions of repo spreads (in basis points) on the z-score our implied interest rate differential measure and a vector of controls including an AR(1) term. Coupon issuance includes bonds and notes. Robust standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 13: **Instrumental variables regressions for repo spreads, Jan 2015 – May 2020.**

	Spread Measure							
	(1) SOFR-IOER	(2) SOFR-IOER	(3) GCF-IOER	(4) GCF-IOER	(5) GCF-TGCR	(6) GCF-TGCR	(7) GCF-EFFR	(8) GCF-EFFR
IR factor	4.60*	4.60*	4.12*	4.14*	0.13	0.14	4.07	4.05
	(2.41)	(2.39)	(2.47)	(2.43)	(0.70)	(0.66)	(2.61)	(2.58)
Coupon issuance	0.03***	0.03***	0.05***	0.05***	0.03**	0.03**	0.04***	0.04***
	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Bill issuance	-0.05***	-0.05***	-0.08***	-0.07***	-0.03**	-0.03**	-0.07***	-0.07***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)
T-bill yield	0.07***	0.07***	0.06***	0.06***	-0.00	-0.00	0.04*	0.04*
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.02)
TGA balances	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.01)
Month-end dummy	6.29***	6.29***	8.12***	8.12***	4.22***	4.21***	13.80***	13.80***
	(1.46)	(1.46)	(1.86)	(1.87)	(1.36)	(1.37)	(1.91)	(1.91)
Income tax payment	0.08	0.08	0.12	0.12	0.06	0.07	0.13**	0.13**
	(0.05)	(0.05)	(0.08)	(0.08)	(0.04)	(0.04)	(0.07)	(0.07)
SOMA net purchases	-0.07	-0.07	-0.09	-0.12	-0.05*	-0.06	-0.16*	-0.13
	(0.06)	(0.12)	(0.07)	(0.16)	(0.03)	(0.10)	(0.09)	(0.16)
OPEC Announcement	-41.95*	-41.96*	-130.24*	-130.41*	-96.94	-97.07*	-115.15**	-114.94**
	(22.12)	(22.05)	(67.73)	(66.93)	(59.15)	(58.66)	(52.19)	(53.88)
Brent return	-4.48	-4.44	1.64	2.18	7.30*	7.65	2.94	2.23
	(12.27)	(13.00)	(14.20)	(15.23)	(4.38)	(5.52)	(14.76)	(15.36)
FOMC announcement	1.84	1.84	2.16	2.13	0.13	0.11	1.93	1.97
	(3.27)	(3.33)	(3.71)	(3.78)	(0.69)	(0.67)	(3.70)	(3.76)
VIX	0.06	0.06	0.08	0.08	0.01	0.01	0.04	0.05
	(0.15)	(0.15)	(0.18)	(0.17)	(0.07)	(0.06)	(0.17)	(0.16)
March 2020		0.14		2.01		1.33		-2.64
		(7.27)		(9.35)		(7.64)		(8.16)
IV F-stat	95.6	95.6	93.6	94.1	84.9	84.9	88.2	88.7
Observations	1257	1257	1257	1257	1256	1256	1257	1257
R^2	0.39	0.39	0.42	0.42	0.56	0.56	0.27	0.27

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 13 summarizes the results of daily instrumental variables regressions of repo spreads (in basis points) on the z-score our implied interest rate differential measure (instrumented for by oil option-implied volatility) and a vector of controls including an AR(1) term for the subsample from January 2015 - May 2020. Coupon issuance includes notes and bonds. Robust standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 14: **Instrumental variables regressions for major holdings of Treasury securities**

	Oil Exporters						All Foreign					
	(1) Tot	(2) Tot	(3) LT	(4) LT	(5) ST	(6) ST	(7) Tot	(8) Tot	(9) LT	(10) LT	(11) ST	(12) ST
IR factor	-1.99***	-2.00**	-1.64***	-1.72***	-0.41	-0.36	-5.55	-6.76	-6.63	-8.54	1.08	1.78
	(0.74)	(0.78)	(0.55)	(0.57)	(0.46)	(0.50)	(5.59)	(5.86)	(5.44)	(5.73)	(2.05)	(2.10)
Coupon issuance	-0.01	-0.01	-0.01	-0.01	0.00	0.00	-0.02	-0.02	-0.01	-0.02	-0.00	0.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.08)	(0.09)	(0.07)	(0.07)	(0.02)	(0.02)
Bill issuance	0.00	0.00	-0.00	-0.00	0.01**	0.00	0.13***	0.17***	0.08**	0.15***	0.05***	0.02
	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.03)	(0.06)	(0.03)	(0.06)	(0.01)	(0.02)
T-bill yield	-0.00	-0.00	0.00	0.00	-0.00	-0.00	0.10	0.08	0.10*	0.08	-0.00	0.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.06)	(0.07)	(0.06)	(0.06)	(0.02)	(0.02)
TGA balances	0.00	0.00	-0.00	-0.00	0.01	0.01	-0.11**	-0.10*	-0.12**	-0.10*	0.01	-0.00
	(0.01)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.06)	(0.06)	(0.05)	(0.05)	(0.02)	(0.02)
Income tax payment	-1.89	-1.89	-2.15***	-2.12***	0.33	0.31	-5.68	-4.95	-7.47	-6.32	1.79	1.37
	(1.27)	(1.29)	(0.79)	(0.77)	(1.04)	(1.04)	(8.56)	(8.80)	(7.60)	(7.97)	(3.50)	(3.53)
SOMA net purchases	-0.05***	-0.05***	-0.03***	-0.03**	-0.02***	-0.02	-0.30***	-0.46**	-0.23***	-0.48***	-0.08***	0.02
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.08)	(0.19)	(0.08)	(0.18)	(0.03)	(0.06)
OPEC Announcement	-29.53	-29.81	-42.41***	-44.15***	13.03	14.16	-345.59	-385.87*	-325.31	-388.87*	-20.29	3.00
	(30.69)	(31.36)	(14.34)	(15.42)	(26.08)	(25.94)	(236.88)	(230.50)	(242.94)	(230.93)	(59.46)	(71.39)
Brent return	-10.33**	-10.17*	-1.72	-0.70	-8.57***	-9.23***	-28.41	-16.13	-7.19	12.20	-21.22	-28.33
	(4.91)	(5.43)	(3.75)	(4.14)	(3.16)	(3.23)	(46.15)	(55.16)	(49.49)	(55.34)	(15.38)	(17.00)
FOMC	2.76	2.74	1.28	1.21	1.37	1.42	-0.08	-0.57	-0.23	-0.99	0.15	0.42
	(1.73)	(1.74)	(1.18)	(1.17)	(1.26)	(1.25)	(10.61)	(11.04)	(10.58)	(11.59)	(4.72)	(4.94)
VIX	-0.18	-0.18	-0.01	-0.02	-0.17	-0.17	1.60	1.51	1.77	1.62*	-0.17	-0.11
	(0.13)	(0.13)	(0.13)	(0.13)	(0.11)	(0.11)	(1.17)	(1.07)	(1.08)	(0.93)	(0.24)	(0.29)
March 2020		0.95		6.00		-3.89		133.44		210.62		-77.18
		(13.38)		(10.21)		(9.38)		(171.83)		(153.27)		(48.65)
Constant	5.21*	5.20*	3.77*	3.69	1.38	1.43	0.50	1.08	1.15	2.06	-0.65	-0.98
	(2.93)	(2.95)	(2.26)	(2.26)	(2.39)	(2.43)	(22.52)	(21.85)	(19.75)	(18.49)	(6.00)	(6.46)
IV F-stat	368	368	368	368	368	368	368	368	368	368	368	368
Observations	92	92	92	92	92	92	70	70	70	70	70	70
R^2	0.64	0.64	0.71	0.71	0.21	0.21	0.46	0.46	0.48	0.49	0.30	0.32

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 14 summarizes the results of monthly instrumental variables regressions of monthly changes ($ billions) in foreign official holdings on the z-score our implied interest rate differential measure (instrumented for by oil option-implied volatility) and a vector of controls for the subsample from January 2010-May 2020. Coupon issuance includes notes and bonds. Robust standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 15: **Instrumental variables regressions for primary dealer Treasury exposure and factors affecting reserves.**

	(1) Foreign repo	(2) Foreign repo	(3) Swap lines	(4) Swap lines
IR factor	1.50***	1.17**	2.05***	0.16
	(0.57)	(0.57)	(0.60)	(0.13)
Coupon issuance	0.03***	0.03***	-0.00	-0.00
	(0.01)	(0.01)	(0.01)	(0.00)
Bill issuance	-0.01**	-0.01	-0.02*	0.01
	(0.01)	(0.00)	(0.01)	(0.00)
T-bill yield	0.01	0.01	0.01**	-0.01**
	(0.01)	(0.01)	(0.00)	(0.00)
TGA balances	-0.01	-0.00	-0.01	0.01**
	(0.00)	(0.00)	(0.01)	(0.00)
Month-end dummy	6.69***	6.54***	0.88	-0.00
	(2.26)	(2.27)	(0.82)	(0.37)
Income tax payment	0.10*	0.11*	-0.02	0.01
	(0.06)	(0.06)	(0.04)	(0.03)
SOMA net purchases	0.04**	-0.02	0.38***	-0.00
	(0.02)	(0.02)	(0.10)	(0.03)
OPEC announcement	-13.44	-14.11	-34.99	-41.59
	(32.36)	(32.83)	(54.60)	(45.68)
Brent return	-9.29	-5.48	-9.10	11.01
	(5.80)	(5.67)	(24.43)	(9.48)
FOMC announcement	2.38**	2.20**	0.88*	0.08
	(1.04)	(1.03)	(0.51)	(0.27)
VIX	-0.07	-0.04	-0.10	0.08*
	(0.12)	(0.12)	(0.15)	(0.05)
March 2020		31.52***		169.22***
		(6.74)		(22.77)
IV F-stat	368	368	368	368
Observations	521	521	521	521
R^2	0.99	0.99	0.97	0.99

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 15 summarizes the results of weekly instrumental variables regressions of weekly primary dealer Treasury exposure and factors affecting federal reserve balances ($ billions) on our implied interest rate differential measure (instrumented for by oil option-implied volatility) and a vector of controls. Robust standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.